# LLOYD'S REGISTER STAFF ASSOCIATION

SESSION
1960-61

# TRANSACTIONS

# OF

# LLOYD'S REGISTER STAFF ASSOCIATION


**VOLUME 31**

1960-61

71 FENCHURCH STREET, LONDON, E.C.3

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For Private Circulation amongst the Staff only

Lloyd's Register
Staff Association

Session 1960 - 61
Paper No. 1

# SOME NOTES ON FREE - PISTON GAS TURBINE MACHINERY FOR MARINE APPLICATIONS

by

R. J. HOOK

LLOYD'S REGISTER OF SHIPPING

71, Fenchurch Street, LONDON, E.C.3

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# Some Notes on Free-Piston Gas Turbine Machinery for Marine Applications

**By R. J. Hook**

The purpose of this paper is to give a brief history of free-piston engine development and to describe some of the machinery features and applications with which the Society is at present concerned, in the hope that it may be of interest to Surveyors.

Free-piston engines have been used for a number of years as air compressors, mostly in France and Germany, but it is only within the last decade that they have been developed as gasifiers and combined with gas turbines to propel ships and therefore so far as marine propulsion is concerned they are a relatively new type of prime mover.

One of the first questions which could reasonably be asked is "What is a free-piston engine?" Basically, the free-piston engine is a two-stroke, uniflow-scavenged, opposed-piston diesel engine that is supercharged by direct-connected reciprocating compressor pistons as shown in Fig. 1. In this system all the reciprocating work produced in the diesel cylinder is absorbed by the compressor pistons and the friction of the moving parts. In addition to supplying air, the compressor pistons also store up energy in the cushion cylinders to stop piston motion at the end of the outward power stroke and to return the pistons to the inner position during the inward compression stroke.

The opposed-piston configuration presents a symmetrically balanced machine where the relative motion of the pistons is controlled by pneumatic forces and no crankshaft or flywheel is used. When the engine is operated as a gasifier all the air from the compressor cylinders at relatively high supercharge pressures of 40 p.s.i. and upwards, passes into the diesel cylinder, where fuel is burned. After combustion and movement of the pistons on the outward power stroke, the gas is exhausted into a gas receiver, or "collector" as it is called, and expanded through a gas turbine to produce useful mechanical work.

### Working cycle of free-piston engines

The gas generator in use for main propulsion purposes at the present time operates on the Pescara system, a single stage inward compressing 2-stroke cycle. The arrangement is shown diagramatically in Fig. 1. The gas generator (A) contains two opposed-piston assemblies, (1) with the diesel power cylinder (2) in the centre. The two single-acting compressor cylinders (4) are located at each end of the central housing. The end spaces (3) constitute the cushion cylinders which store the energy for the return stroke. Fresh air is drawn through the suction valves (5) and is delivered through the discharge valves (6) into the engine case which surrounds the diesel cylinder. The fuel is injected through six injectors mounted in a central position relative to the combustion chamber.

Fig. 1 may also be used to describe the processes that occur during each cycle. In order to start the engine the pistons are first positioned at the outer dead point (O.D.P.) as shown in the figure. Compressed air from a starting-air receiver is admitted to the cushion cylinders thus driving the pistons to the centre. Fuel is injected as the pistons approach their inner dead point (I.D.P.) and combustion occurs. As the compressor pistons approach their I.D.P. the discharge valves (6) open to admit the compressed air to the engine case. The gas pressure due to combustion, added to the pressure of air remaining in the clearance space of the compressor cylinders, drives the pistons outwards, compressing the air in the cushion cylinders (3). The work done during the outward stroke is represented by the vertically shaded area in the pressure/volume diagrams (10) and (12) for the engine and compressor cylinders. This work is subsequently recovered except for friction, radiation and losses to the cooling medium and is shown in the pressure/volume diagram (11) for the cushion cylinder.

As the pistons move outwards the exhaust ports shown on the right are uncovered first, followed by the scavenge air ports. The resulting exhaust gas combined with excess scavenging air then flows through a gas collector (B) which serves to smooth out the pulsation to the power turbine (C) where the gas is expanded almost to atmospheric pressure. As soon as the pressure in the compressor cylinders (4) has dropped to about atmospheric pressure, the suction valves (5) open and fresh air enters the compressor cylinders. As the pistons approach the O.D.P. the increase of pressure in the cushion cylinders stops outward motion and the inward compression stroke begins. When the diesel pistons cover the exhaust and scavenge ports, the scavenging process ends. At this point the trapped air in the diesel cylinder is momentarily at the same pressure as the gas collector since the exhaust ports close last on the inward stroke. As compression continues the pistons come to rest at the inner dead point and the cycle is repeated. The energy stored in the cushion cylinders is expended in providing the work done on the inward compression stroke, both in the compressor and power cylinders and in associated losses. The work done on the inward stroke is illustrated by the horizontally shaded areas on the pressure/volume diagrams.

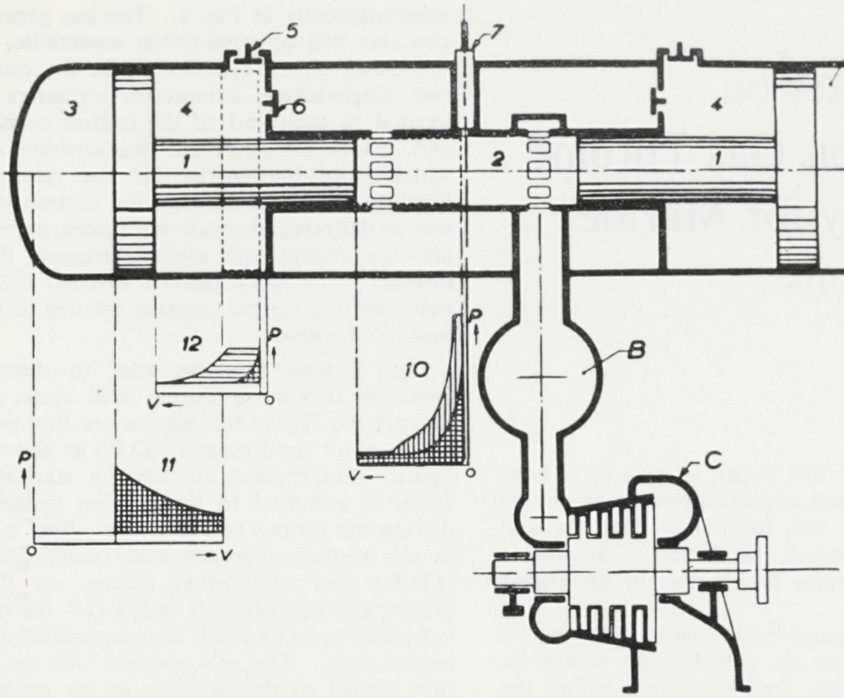



Fig. 1

Diagrammatic sketch of a free-piston gas generator and gas turbine, showing pressure-volume diagrams of the engine, compressor and cushion cylinders. A—Gas generator; B—Gas collector; C—Gas turbine; 1—Piston; 2—Engine cylinder; 3—Cushion cylinder; 4—Compressor cylinder; 5—Suction valves; 6—Delivery valves; 7—Fuel injector; 10—*P–V* diagram of engine cylinder; 11—*P–V* diagram of cushion cylinder; 12—*P–V* diagram of compressor cylinder

**History**

The principle of the free-piston engine has been known for over 100 years and numerous references may be found in the literature on the subject. In 1857 Barsanti and Matteucci proposed a free-piston gas engine which consisted of a vertical cylinder open at the top and containing a heavy piston that was coupled by means of a chain to a ratchet wheel, on which useful mechanical work was performed on the down stroke. While this proposal failed to develop into a practical engine, Otto and Langlen exhibited a similar engine at the 1867 Paris Exhibition.

Under their persistent efforts this engine remained for about 10 years the most economical and reliable but noisiest gas engine of its type on the market. In 1912 Professor Junkers is reported to have given a talk before a German naval engineering society on free-piston machinery. During the first quarter of this century a number of British, French and German patents on free-piston applications were filed and since then several companies have experimented with varying degrees of success.

Shortly after World War I Marquis Raul de Pateras Pescara was searching for a light-weight engine/compressor unit to provide compressed air to drive a helicopter rotor by means of reaction jets. There were no existing machines of this type available and he developed his own design in the form of a free-piston engine/compressor unit. Whilst the machine did not develop into a practical helicopter application, it later evolved into a commercial free-piston compressor unit which in time led to the free-piston gasifier concept.

Pescara started development work on free-piston engines about 1922 and shortly after assembled a group of engineers under the direction of R. Huber to design free-piston machinery. The first experimental compressor was built in Paris about 1925. Around the same time it is understood that the first free-piston compressors actually built and used were made by Junkers in Germany and Breguet in France. During this early period and up to about 1939 development appears to have been limited to free-piston air compressors. In 1941 the Société Industrielle Générale de Mécanique Appliqué (S.I.G.M.A.) became a sub-licensee of the Pescara patents and built free-piston compressors.

Design work on free-piston gasifiers began about 1933 and in 1937 the Société d'Études et de Participations (S.E.P.) of Geneva, Switzerland became a licensee under Auto Compresseurs Pescara (A.C.P.) from whom also Alan Muntz &

# World distribution of manufacturing rights[1] in the Pescara Free-Piston Engine System

**Pescara and A.C.P.**[2]

**1922**—World rights vested in A.C.P. by the Marquis R. de Pateras Pescara.

**LICENSEES**

**S.A.C.M.**,[3] 32 rue de Lisbonne, Paris, France.

**1934**—Exclusive rights for France, Belgium and their overseas territories. Licence taken over by S.E.P. in 1940.

**S.E.P.**,[4] 12 rue Diday, Geneva, Switzerland, of which **S.E.M.E.**,[6] 61 Ave. F. D. Roosevelt, Paris 8e, France, is the design and development organisation.

**1937**—Exclusive rights for world except British Commonwealth,[5] Eire, Egypt, France, Belgium and their overseas territories.

**1940**—Licence extended to cover S.A.C.M. territory.

Agreement signed in May, 1937, providing complete technical reciprocity and granting mutual and exclusive patent rights for each other's country.

**Alan Muntz and Co., Ltd.**, Browells Lane, Feltham, Middx., England.

**1936**—Exclusive rights for British Commonwealth,[5] Eire and Egypt.

**SUB-LICENSEES** (S.E.P.)

- **1937**—**S.I.G.M.A.**,[7] 61 Ave. F. D. Roosevelt, Paris 8e. All applications.
- **1942**—**Chantiers de l'Atlantique**, 7 rue Auber, Paris 9e. Marine and stationary applications.
- **1949**—**Chantiers et Ateliers Augustin-Normand**, 27 rue de la Mailleraye, Le Havre, France. Marine applications.
- **1949**—**Regie Nationale des Usines Renault**, 8 Ave. Emile Zola, Billancourt, Seine, France. Locomotive applications. (In association with Forges de la Loire.)
- **1950**—**Ateliers et Chantiers de la Seine Maritime**, 47 Boulevard Haussmann, Paris 9e. Marine applications.
- **1954**—**Cie. des Ateliers et Forges de la Loire**, 12 rue de la Rochefoucauld, Paris 9e. Locomotive applications. (In association with Renault.)
- **1955**—**Forges et Chantiers de la Mediterranee**, 25 Boulevard Malesherbes, Paris 8e. Marine applications.
- **1956**—**Demag Aktiengesellschaft**, 64 Werthauser Strasse, Duisburg, Germany. All applications.
- **1956**—**Amsterdamsche Droogdok Maat. N.V.**, Amsterdam, Holland. Marine and industrial applications. (In association with Werkspoor.)
- **1956**—**Werkspoor N.V.**, Amsterdam, Holland. Marine and industrial applications. (In association with Amsterdamsche Droogdok.)
- **1956**—**General Motors Corp.**, Detroit, U.S.A. Non-exclusive for S.E.P. territory, exclusive rights for limited period.
- **1958**—**Nippon Kokan Kabushi Kaisha.** Non-exclusive for Japan and China.

**SUB-LICENSEES** (Alan Muntz and Co., Ltd.)

- **Jan., 1953**—**Charles D. Holmes and Co., Ltd.**, Hull, Yorks. Non-exclusive for gasifiers weighing over $4\frac{3}{4}$ lb./g.h.p. for marine and industrial applications. Exclusive for trawler and tug applications.
- **Nov., 1953**—**Smith's Dock Co., Ltd.**, Middlesbrough, Yorks. Non-exclusive for gasifiers weighing over $4\frac{3}{4}$ lb./g.h.p. for marine and industrial applications. Exclusive for whale-catcher application.
- **Jan., 1955**—**Mackay Industrial Equipment, Ltd.**, Faggs Road, Feltham, Middlesex. Exclusive for compressors delivering between 90 and 400 c.f.m. only.[8]
- **Feb., 1956**—**Associated British Engineering Co., Ltd.**, 41 Bedford Row, London, W.C.1. Non-exclusive for industrial, marine and locomotive applications. Exclusive for gasifiers using power cylinder bores under 6 in., non-exclusive above 6 in.[10]
- **June, 1956**—**Alexander Stephen and Sons, Ltd.**, Linthouse, Glasgow. Non-exclusive for marine and industrial applications using power cylinder bores over 6 in.
- **Aug., 1956**—**General Motors Corp.**, Detroit, U.S.A. Non-exclusive for British Commonwealth, Eire and Egypt. Exclusive rights in Canada for limited period.
- **Oct., 1956**—**National Gas and Oil Engine Co., Ltd.**, Ashton under Lyne, Lancs. Non-exclusive for industrial, marine and locomotive applications using power cylinder bores over 6 in.[11]
- **Feb., 1957**—**Lithgow Power Development Co., Ltd.**, Greenock, Scotland. Non-exclusive for marine and industrial applications using power cylinder bores over 6 in.
- **Feb., 1958**—**Swan, Hunter & Wigham Richardson, Ltd.**

NOTES:

1. Other arrangements are in force concerning selling rights.
2. Auto Compresseurs Pescara.
3. Société Alsacienne de Constructions Mécaniques.
4. Société d'Etudes et de Participations.
5. As existing in 1937.
6. Société d'Etudes Mécaniques et Energétiques. Formed in 1938 when S.E.P. took over the Pescara patent rights, this concern continues the work of the Bureau Technique Pescara under the direction of M. Huber.
7. Société Industrielle Générale de Mécaniques Appliquée. This concern is the leading S.E.P. sub-licensee and in association with S.E.M.E. has been responsible for the development of the GS-34 gasifier.
8. Approved manufacturers: Henry Meadows, Ltd., Fallings Park, Wolverhampton, Staffs.
9. Gasifiers to be manufactured by subsidiary Lithgow companies.
10. Design, development by the Free Piston Engine Co., Ltd.; manufacture by members of the A.B.E. Group, e.g., British Polar Engines, Ltd., Govan, Glasgow.
11. Gasifiers to be marketed by National Free Piston Power, Ltd., a new subsidiary of the Brush Group.

**General:** With the exception of Mackay and General Motors, all A.M. agreements refer to gasifiers only; S.I.G.M.A. and General Motors licences cover compressors. All A.M. sub-licences call for assembly only in Canada, not manufacture.

Fig. 2

Co. Ltd., of Middlesex, England, obtained their licence. In 1938 the Société d'Études Mécaniques et Energetiques (S.E.M.E.) was formed by S.E.P. as a design and development group under the direction of R. Huber. S.I.G.M.A. became the leading sub-licensee under S.E.P. in 1937 and the S.I.G.M.A. group in association with S.E.M.E. have largely been responsible for the development of the G.S.34 gasifier now in use.

In the United Kingdom a smaller type, known as the C.S.75 of the same general construction as the G.S.34 has been developed by Messrs. Alan Muntz & Co. Ltd., which produces sufficient power to drive a 200 kW gas turbo-generator.

It is only in the past decade that the free-piston engine has begun to occupy a position in the marine engineering world and the marked increase in the number of sub-licensees in the last ten years may be seen from the table in Fig. 2.

In the past 10 years also free-piston gas generators of the G.S.34 type have been developed in the U.S.A. by the Baldwin Lima Hamilton Corporation and six units of this type manufactured by the General Motors Corporation are installed in the G.T.V. *William Patterson,* a Liberty ship converted under the U.S. Maritime Administration programme and equipped with main propulsion gas turbine machinery of 6,000 s.h.p.

At the time of writing, ships classed with the Society and having free-piston gas turbine main propulsion machinery are the G.T.V. *Morar,* G.T.V. *Goodwood,* G.T.V. *Rembrandt* and G.T.V. *Robert W. Vinke,* and it is understood two further conversions may be carried out in due course. Extracts from the Register Book giving the main particulars of the first four vessels are shown on page 5.

Two French coasting vessels classed with Bureau Veritas, the *Cantenac* and *Merignac* of 1,800 s.h.p. have been in service since 1954 and there are also a number of minesweepers in service with the French Navy fitted with free-piston gas turbine machinery.

In Germany a trawler classed with Germanischer Lloyd, the *Sagitta,* is equipped with G.S.34 type free-piston machinery and in Russia there are reported on order, six marine propulsion sets each of 4,000 s.h.p.

In Holland two fruit carrying cargo ships the *Geestland* and *Geestar* have recently entered service propelled by free-piston gas-turbine machinery of 4,000 s.h.p.

Figs. 3 and 4 show longitudinal sections of a G.S.34 unit having the following main particulars: —

| | |
|---|---|
| Diesel cylinder bore ... ... | 340 mm. |
| Compressor Cylinder ... ... | 900 mm. |
| Stroke at max. con. rating = 2 × 452 mm. ... | 904 mm. |
| Oscillations/min. at M.C.R. ... | 570 |
| Mean piston speed ... ... ... | 1650 ft./min. (503 metres/min.) |
| Compression Pressure ... ... | 1000 p.s.i. (70·4 kg./cm.$^2$) |
| Max. Combustion Pressure ... | 1700 p.s.i. (119·5 kg./cm.$^2$) |
| Gas Delivery Pressure ... ... | 45 to 50 p.s.i. (3·16 to 3·5 kg./cm.$^2$) |
| Gas Temperature at M.C.R. ... | 850° F. (454° C.) |
| Diesel Cylinder Compression Ratio | 9 to 1 |
| M.I.P. ... ... ... ... ... | 180 p.s.i. (12·65 kg./cm.$^2$) |
| Gas Horse Power at M.C.R. ... | 1250 |
| Overall length ... ... ... ... | 14 ft. (4·27 metres) |
| Weight ... ... ... ... ... | 8 tons (8140 kgs.) |

| 1<br>No. in 1960/61 Book | 2<br>SHIP'S NAME<br>Late names, if any<br>Navigational aids | 3<br>TONS<br>Gross<br>Net<br>Summer Deadwt | 4<br>OWNERS Flag<br>Managers Port of Registry | 5<br>CLASSIFICATION<br>Latest SS recorded | 6<br>HULL<br>Type / Date of build<br>Shipbuilders / Where built<br>Length overall, Breadth extreme, Draught summer / Decks<br>Special features<br>Alterations | 7<br>MACHINERY<br>Engines Size Type<br>Enginebuilders Where built<br>Boilers |
|---|---|---|---|---|---|---|
| 62706 | **GOODWOOD**<br>DF ESD RDR | **2496**<br>1285<br>3485 | WM. FRANCE, FENWICK & CO. LTD. British<br>London | ✠**100A1** SS 3/59<br>✠LMC | GT 10–**1949**<br>S. P. Austin & Son Ltd. Sld<br>314′ 11″ 45′ 0″ 18′ 7¾″ 1 dk ptEW | 2 free piston gas generators 2SA 340×904 mm & 1 gas turbine DR geared to sc. shaft ✠NE3/59<br>Smith's Dk Co. Ltd. Mdb<br>&Soc.Gen.desCon.Alsthom Belfort<br>✠2ndb 3/59–150lb |
| 72588 | **MORAR**<br>DF ESD GC PFD RDR RT | **6990**<br>3100<br>9000 | SCOTTISH ORE CARRIERS LTD. British<br>J. & J. Denholm (Management) Ltd. Greenock | ✠**100A1**<br>ore carrier<br>✠LMC | GT Ore Carrier Mchy.aft 1–**1959**<br>Lithgows Ltd. P.Gl<br>427′ 0″ 57′ 3″ 25′ 3½″ 1 dk LF ptEW<br>NS in dry cargo hold fwd | 3 free piston gas generators 2SA 340×904 mm & 1 gas turbine DR geared to sc. shaft<br>British Polar Engines Ltd. Gls<br>Rankin & Blackmore Ltd. Grk<br>db 100lb |
| 77299 | **REMBRANDT** | **7700**<br>4000<br>12500 | BOLTON STEAM SHIPPING CO. LTD. British<br>London | **100A1**<br>Class contemplated | GT Mchy.aft<br>Smith's Dock Co. Ltd. Mdb<br>491′ 6″ 63′ 3″ 27′ 6″ ptLF ptEW | 5 free piston gas generators 2SA 340×904 mm & 1 gas turbine DR geared to sc. shaft<br>Smith's Dk Co. Ltd. Mdb<br>British Thomson Houston Rugby |
| 77841 | **ROBERT W. VINKE** | **650**<br>300<br>— | NEDERL. MAATS. VOOR DE WALVISVAART N.V. Netherland<br>Vinke & Co. Amsterdam | **100A1**<br>whaler<br>Class contemplated | GT Whaler Mchy.aft<br>N.V. Ijsselwerf Rot<br>205′ 3″ 32′ 3″ 13′ 1½″ ptEW | 3 free piston gas generators 2SA 340×904 mm & 1 gas turbine DR geared to sc. shaft<br>Amsterdamsche D.D. Maats. Ams |

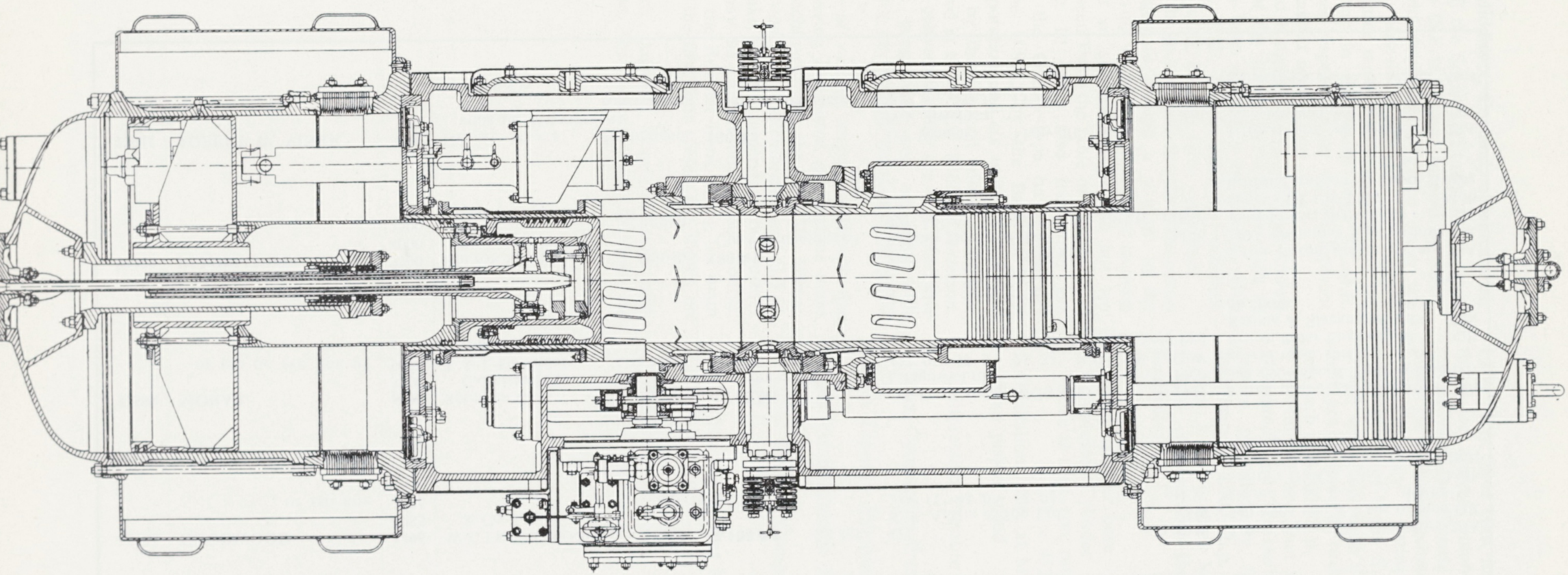


Fig. 3
Longitudinal horizontal section of G.S.34 free-piston gas generator

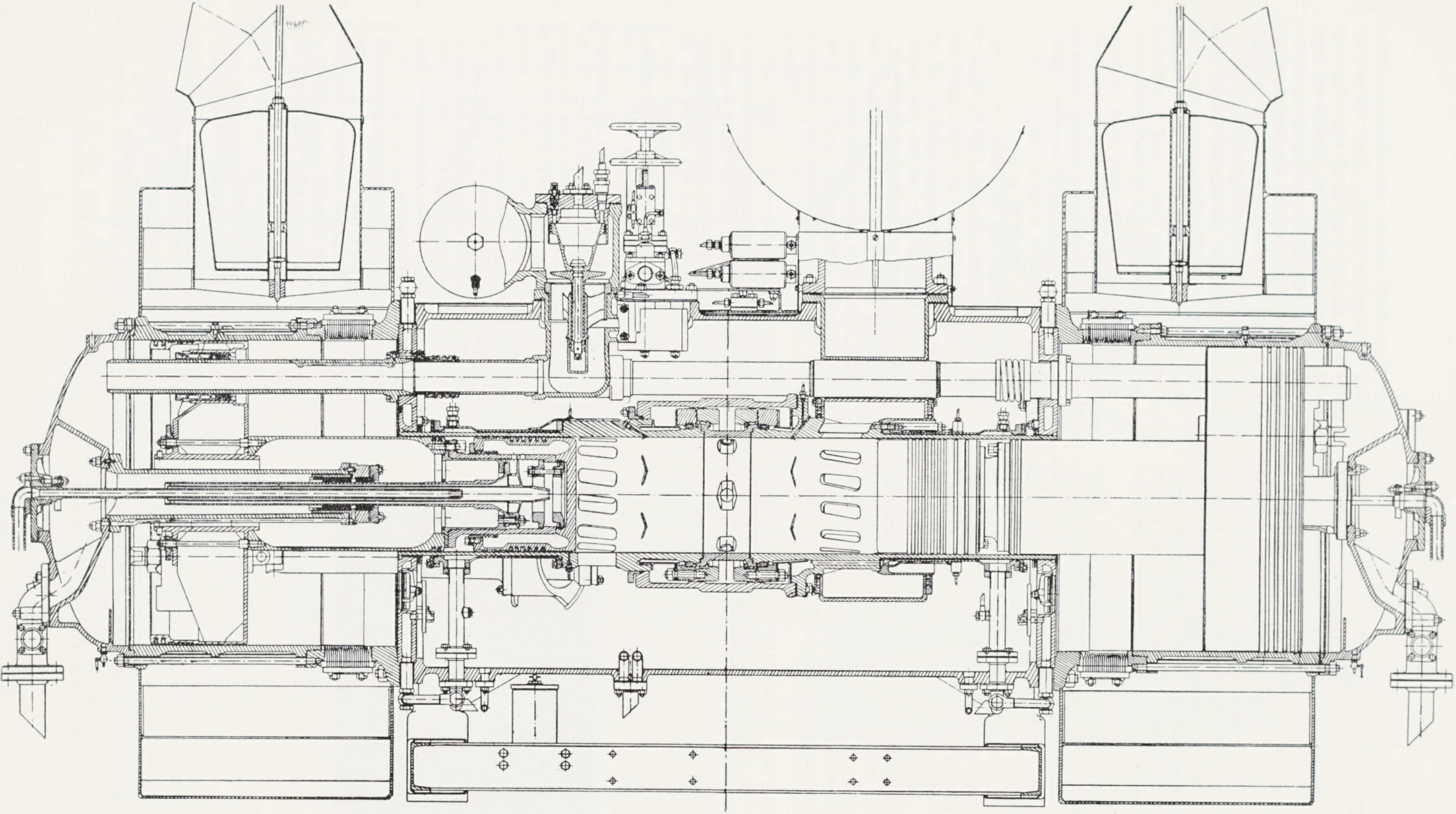


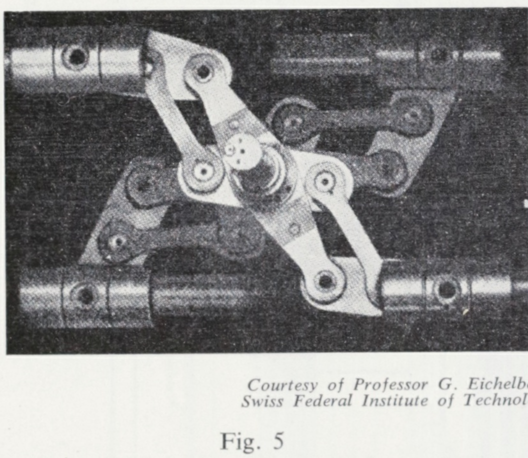
Fig. 4
Longitudinal vertical section of G.S.34 free-piston gas generator

It may be seen from Figs. 3 and 4 that the G.S.34 unit consists of a horizontal single cylinder opposed-piston 2-SCSA diesel engine connected via a cylindrical piston trunk to a reciprocating air compressor piston, the gas load being transmitted by this method of construction directly to the compressor. The high combustion pressure acting on the diesel pistons overcomes the inertia of the reciprocating parts but does not have to be withstood by the body of the engine. The radial pressure-loading in the combustion space induces a hoop stress in the central zone of the diesel cylinder liner and this of course is designed to withstand it.

The cushion cylinder is subjected to a maximum pressure of about 95 p.s.i. in absorbing the outward momentum of the moving parts, the ratio of maximum to minimum pressure being about 2·7 to 1. The power output of a free-piston gas generator is controlled, of course, by the quantity of fuel injected per working stroke and as this increases or decreases, so the engine stroke varies accordingly, and this governs the mass of gas exhausted to the turbine.

The pistons of a free-piston gas generator are free in the sense that their strokes are controlled only by the gas forces acting upon them and not by a link mechanism such as a crank and connecting rod as in the conventional reciprocating engine.

In actual fact there is a mechanical connection between the reciprocating parts which consists of a synchronising mechanism to keep the two sets of pistons in step (*see* Fig. 5). One set of synchronising links has been found sufficient and these are made quite light and do not transmit any load except that required to drive the fuel injection pump mounted on the engine.



*Courtesy of Professor G. Eichelberg, Swiss Federal Institute of Technology*

Fig. 5

Synchronising rods and linkages in their end positions

An advantageous feature of the engine is the achievement of mass balance between the two piston assemblies moving in precise opposition. This results in absence of vibration of the reciprocating parts, eliminating the need for heavy engine foundations. But this comment must be qualified to some extent since there are other possible sources of vibration. These include the inertia of the exhaust gases which leave the diesel cylinder at high velocity when the exhaust ports open, thus re-acting on the engine and associated gas ducting. Pulsation at the air compressor intakes may also occur but this can be overcome by the extension of the inlet ducting in a convenient manner so that the air intake takes place external to the machinery space.

Many of the mechanical features of the G.S.34 unit can be seen from Figs. 3 and 4, including the oil-cooling arrangement of the diesel piston, the detachable compressor head plate arranged so that it can be removed complete with delivery valves through the compressor cylinder bore, the piston assemblies, engine case, cushion balance pipe and so on.

## Characteristics and Performance

The characteristics of the G.S.34 unit are shown on Fig. 6.

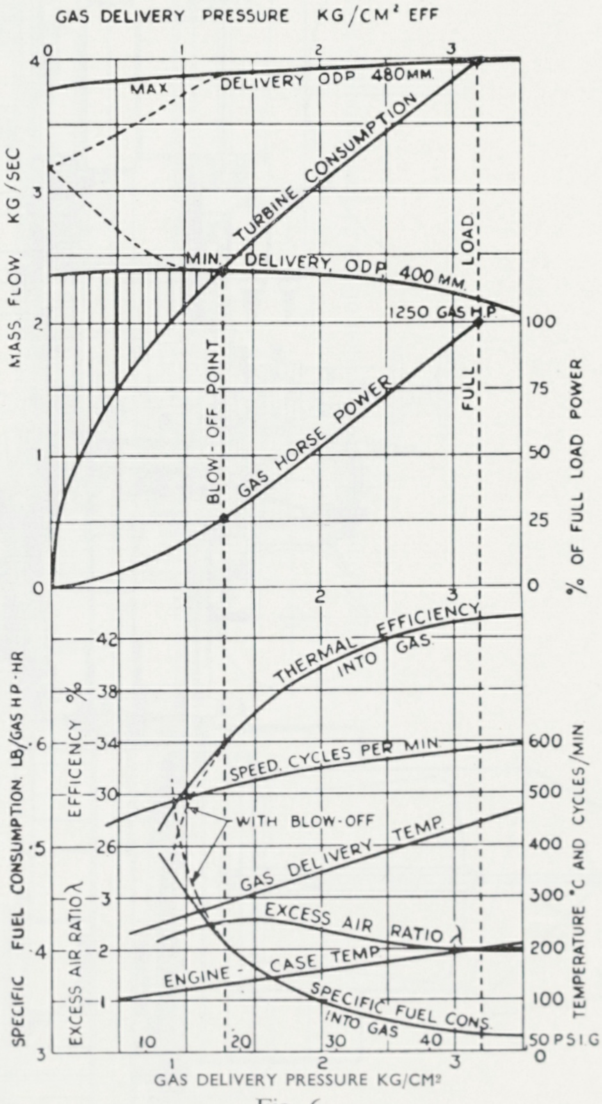



Fig. 6

Characteristics of G.S.34 gas generator

The power output is controlled by varying the stroke and in the normal arrangement with the gas generator supplying a turbine, an increase in gas flow results in an increase in delivery pressure (since the turbine acts approximately as an orifice of constant area), whilst at the same time the gas delivery temperature rises.

The power output is proportional to the mass flow m, the temperature T and the adiabatic heat drop and may be written: —

$$\text{Gas H.P.} \propto m \times T \left[1 - \left(\frac{P2}{P1}\right)^{\frac{r-1}{r}}\right]$$

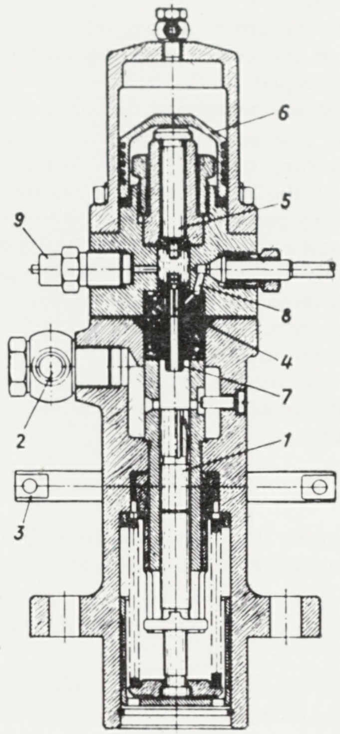
The combined effect of these three variables is that the power varies over a wide range for a small change in stroke as can be seen from Fig. 6. For example, a drop in power from 100 per cent to 25 per cent is produced by a reduction in stroke of about 20 per cent. The clearance volume of the compressor is made up partly by the fixed volume in the delivery valves and partly by the variable clearance between the compressor piston face and the cylinder head (in this case the delivery valve plate) at the Inner Dead Point. At full load the latter is about five per cent of the stroke, and is as small as possible and at low loads as large as possible consistent with an adequate compression pressure in the diesel cylinder.

The I.D.P. is determined by the pressure in the cushion cylinder and this is maintained at the required value by the stabiliser mechanism, dependent on the gas delivery pressure required, and by this means the length of stroke is controlled.

The range of gas delivery is not so flexible as is desirable, since the stroke variation is limited at the low end by the practical necessity of opening the scavange ports adequately to obtain proper scavenging of the diesel cylinder. The scavenge ports must obviously be set at a point giving a good length of effective stroke in the diesel cylinder. As a result the minimum stroke is quite large and there is a point below which the turbine (when low power is required) cannot accept the whole output from the gas generator and so the excess gas must be blown off, this point being known as the blow-off point.

The fuel for combustion is injected by means of a form of accumulator pump shown in Fig. 7 which pumps the required metered quantity of fuel into a storage cylinder, the plunger of which is loaded to the required pressure by compressed air acting on a large piston.

The fuel injection is started just before the I.D.P. by the mechanical opening of a poppet type timing valve which opens the connection to the injectors. The injectors are of conventional type with inward opening differential spray valves, each nozzle having several holes to give a fan shaped spray pattern. There are six injectors on the G.S.34 gas generator, four of which inject direct into the cylinder and two injecting about 5 per cent of the total fuel into pre-combustion chambers.




*Courtesy of Professor G. Eichelberg, Swiss Federal Institute of Technology*

Fig. 7

Fuel accumulator pump

The combustion conditions are such that there is a high degree of supercharging and a good excess air ratio. (See Fig. 6).

The gas delivery temperature depends on the delivery pressure and as shown in Fig. 6 reaches about 850°–900° F. at full load for an ambient temperature of 60° F. and it naturally rises with increase in ambient temperature. A change in atmospheric temperature has no disadvantageous effect on the power output because there is plenty of excess air for combustion in the diesel cylinder.

The gas delivery pressure at full load is in practice limited by a number of considerations. One is the temperature of the air delivered by the compressors into the engine case or scavenge air receiver. If this is too high, above about 428°–466° F. (220°–230° C.), the lubricating oil carried through with the air tends to decompose and produces carbonaceous deposits on the delivery valves and on the walls of the engine case. The valves then gradually become choked and the oily carbon on the walls of the engine case may reach a condition where it may be ignited by a spark blown back through the scavange ports. The danger can be avoided to some extent by keeping the surfaces in contact with the oil-laden air below the critical temperature, and it is for this reason that the compressor head plate carrying the delivery valves is water cooled, and the exhaust belt separated from the rest of the engine case.

The total cooling losses in the G.S.34 amount to about 18 per cent of the total heat in the fuel.

Of this about five per cent is represented by the heat loss to the piston-cooling oil. Thus in a gas generator of the G.S.34 type the heat in the gas delivered is equal to the heat in the fuel minus the heat lost to cooling and radiation, etc.

However, it is perhaps useful to realise that the gas temperature by itself is no criterion of the efficiency of the free-piston engine, since at any given delivery pressure the higher the compressor efficiency and the higher the combustion efficiency, the lower will be the fuel consumption per pound of air delivered. The high pressure and high temperature part of the cycle is carried out in the diesel cylinder (about 1,700 p.s.i. and 2,800° F.) pressures and temperatures far higher than any straight marine gas turbine will be likely to reach for some time.

**Controls**

The controls for the free-piston gas turbine power plant fall into two main categories:—

1. Individual controls on each gas generator for starting, stopping and for adjustment whilst running.

2. Overall controls for the plant as a whole including the turbine.

(1) Individual controls

These consist of:—

(a) The cushion air control or "stabiliser" which maintains the correct pressure in the cushion cylinder to give the required energy to the pistons so as to control the required I.D.P. and compression in the diesel cylinder under all working conditions, i.e., to accommodate the variations in gas pressure and stroke as the load on the machine changes. The mechanism incorporates a slide valve controlled by differential piston and spring, balancing the cushion pressure against the engine case pressure.

(b) The fuel control on each gas generator governs the power output, which is effected by altering the length of stroke and thus the position of the Outer Dead Point. The maximum fuel must be limited as in any diesel engine but there is also a minimum permissable quantity of fuel to avoid too short a stroke since the position of the O.D.P. must be such as to allow the scavenge ports to open adequately.

(c) By virtue of the restricted range of stroke referred to above, when reduced power is required, lower than the minimum which can be delivered by the gas generator, it is necessary to provide some means of dispersing the excess power. As previously stated this is done by means of a gas blow-off valve which permits the unwanted power to be disposed of. This valve is also used when one of a number of gas generators in a set is to be started whilst the others are running so as to avoid starting up against a back pressure. A gas stop valve is also provided to isolate any gas generator from the common manifold.

A "recirculation" valve Fig. 8 may also be fitted to discharge excess scavenge air from the engine case back to the compressor intake.

This has the effect of raising the temperature of the scavenge air, so enabling the engine to run at a lower compression pressure or a larger I.D.P., and thus at a reduced stroke. This in turn reduces the amount of air pumped by the compressor. In this way the power of the gas generator is reduced and the rate of oscillations decreased. The two effects reduce fuel consumption at low loads and when idling.

A by-pass valve may also be used to pass some of the scavenge air from the engine case direct to the gas collector at low and intermediate delivery pressures when there is more air than is required to scavenge the diesel cylinder.

(2) Overall controls

The overall controls are as shown in Figs. 9 and 9a.

A double-seated valve is used for controlling the reversing turbine in marine propulsion sets, fitted with such a turbine, the valve body having outlets to both the ahead and astern turbines. The valve is normally on either the ahead or astern seats but when manœuvring or at low power the valve is partially open to both turbines simultaneously, so that their torques oppose each other and in this way the turbine output can be controlled smoothly and continuously down to zero if necessary without stopping the gas generators. The time required for reversing the turbines depends on the inertia of the rotating components of the system, i.e., rotor, gearing, shafting, and propeller, but it has been stated that the reversing valve can be changed over in about four seconds.

The foregoing comprises a general description of the gas generator unit fitted in vessels having free-piston gas turbine main propulsion machinery now classed or building to class with the Society. Some details of these installations are given below.

**G.T.V. "Morar"** (Fig. 10)

This vessel, an ore carrier, was built by Lithgow's Ltd., for Scottish Ore Carriers Ltd., and is the first British free-piston engined ship. The main propulsion machinery consists of three G.S.34 gas generators supplying gas to an axial-flow turbine built by Rankin and Blackmore Ltd. to the design of Power Jets (Research and Development) Ltd.

The incoming combustion air to the gas generators is ducted down from the boat deck, to overcome the inconvenience due to pulsation at the gasifier intakes in the engine room. The air then enters a spray-excluding baffle chamber at the forward side of the funnel through large slots Fig. 11 and then passes into twin internal intakes with venturi-type acoustic silencers. Two 30 in. axial supply fans then deliver the air through downcomers to a manifold which leads to the gasifier compressor intakes at the ends of each machine. It is understood that when the trunking is adequately stiffened no pulsation is evident.

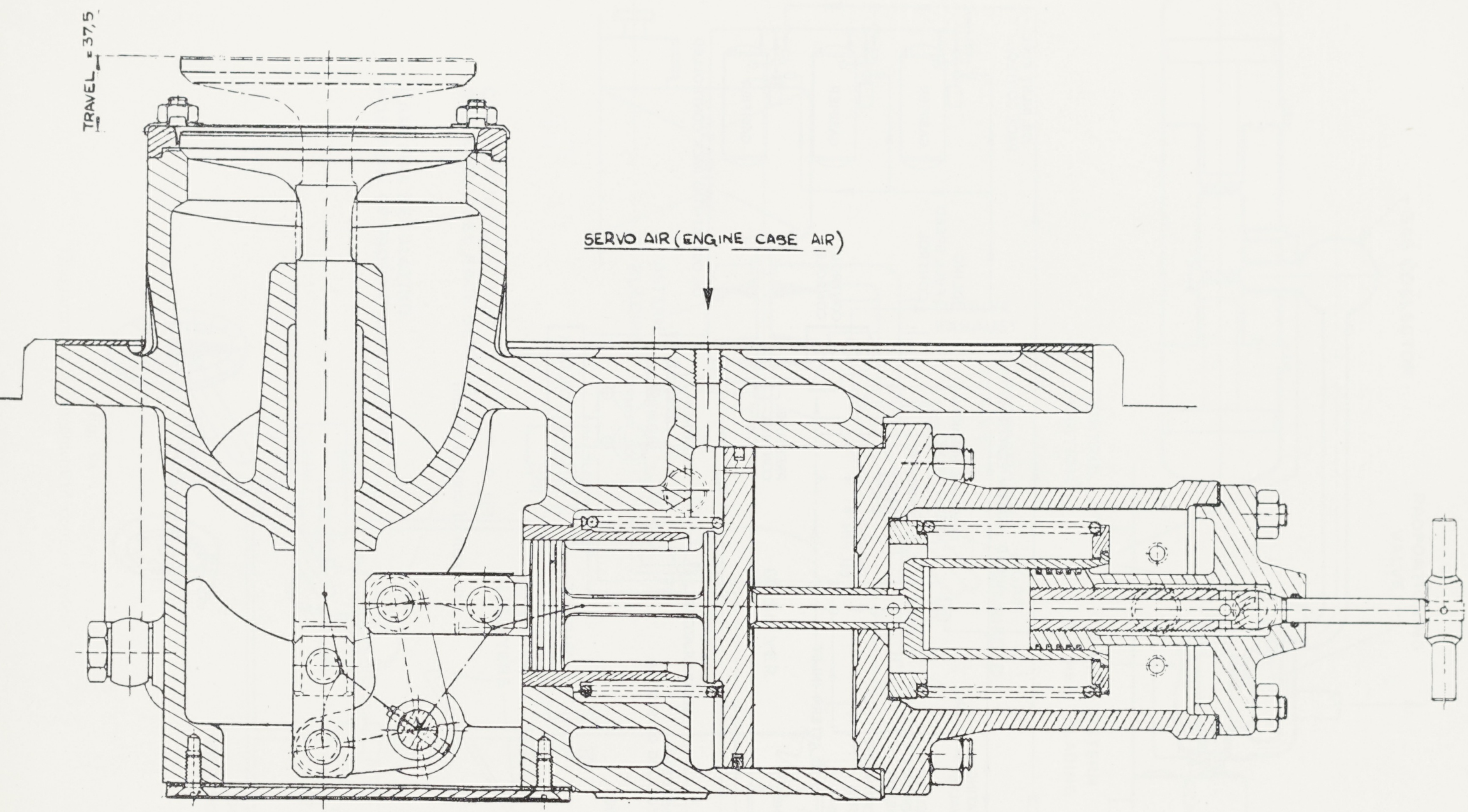



Fig. 8
Recirculation valve

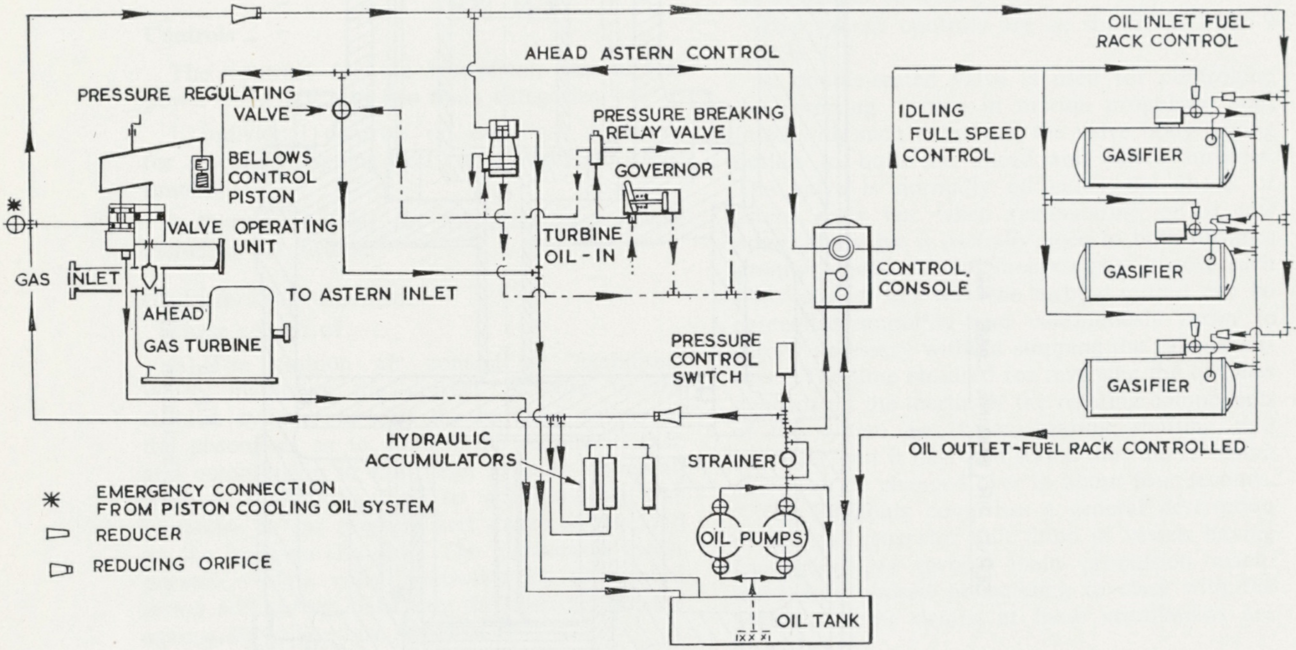



Fig. 9
Diagram of control system

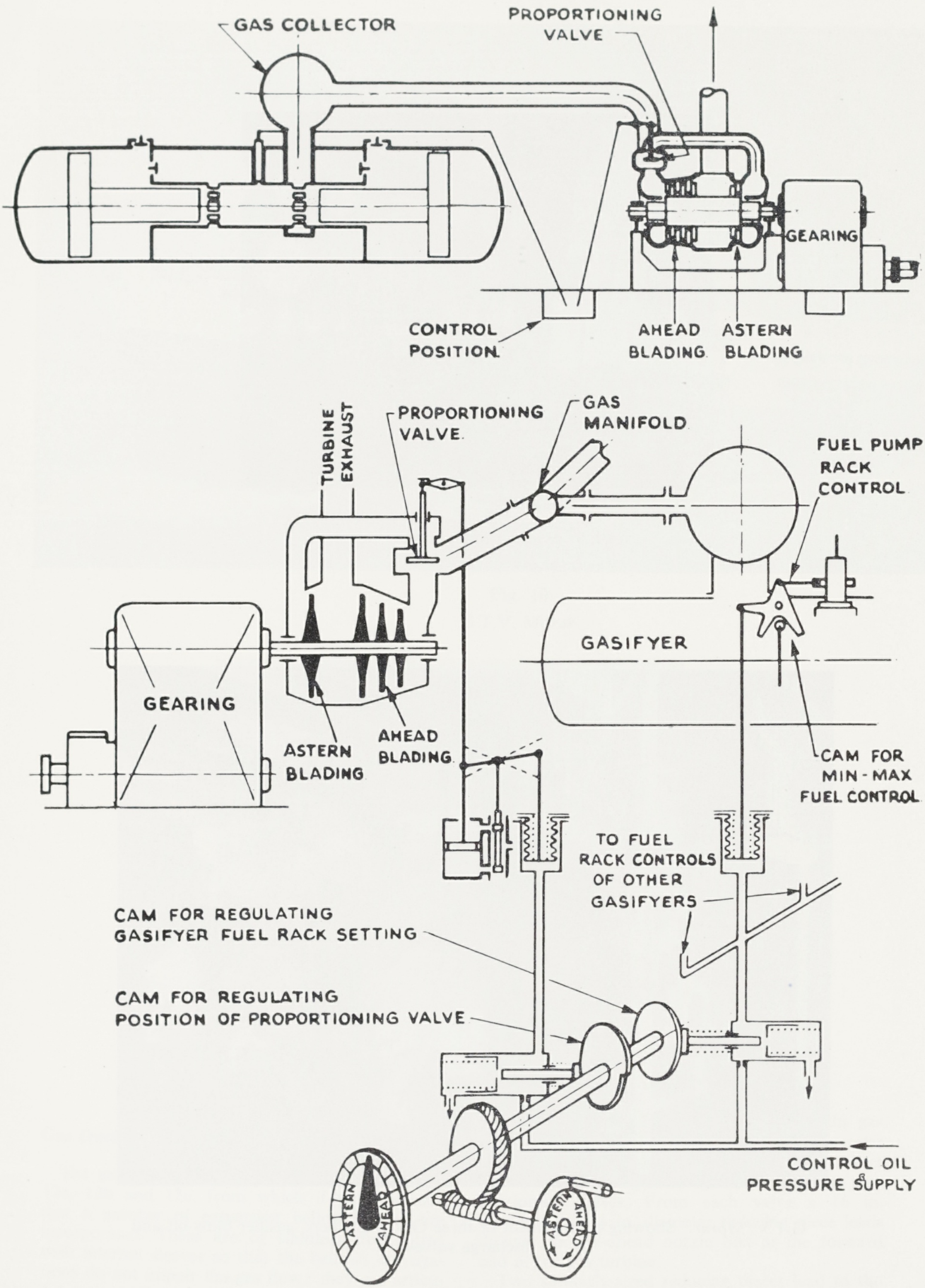



Fig. 9A

Diagrammatic arrangement of control system

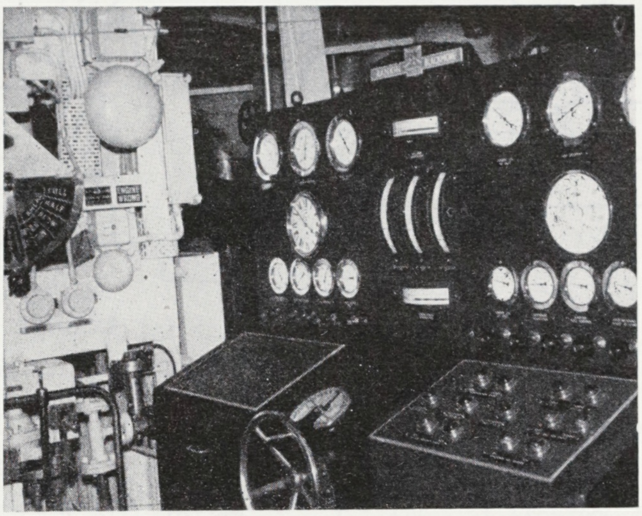


Fig. 9B

G.T.V. *Morar*. Main control panel

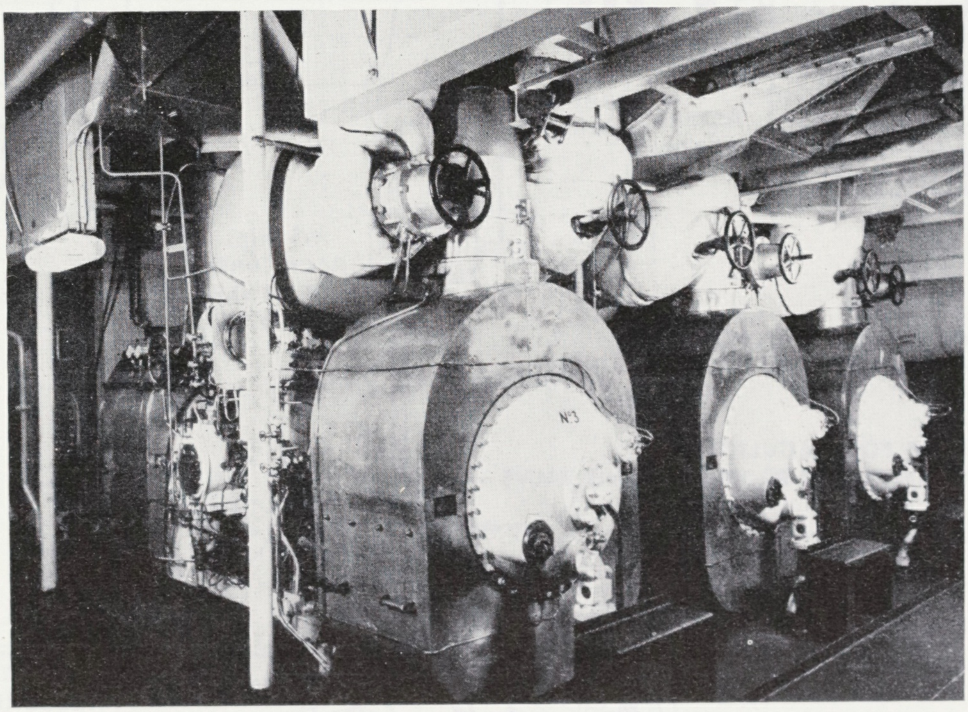



Fig. 9C

G.T.V. *Morar*. Showing arrangement of three G.S.34 gasifiers, gasifier blow-off and discharge valves

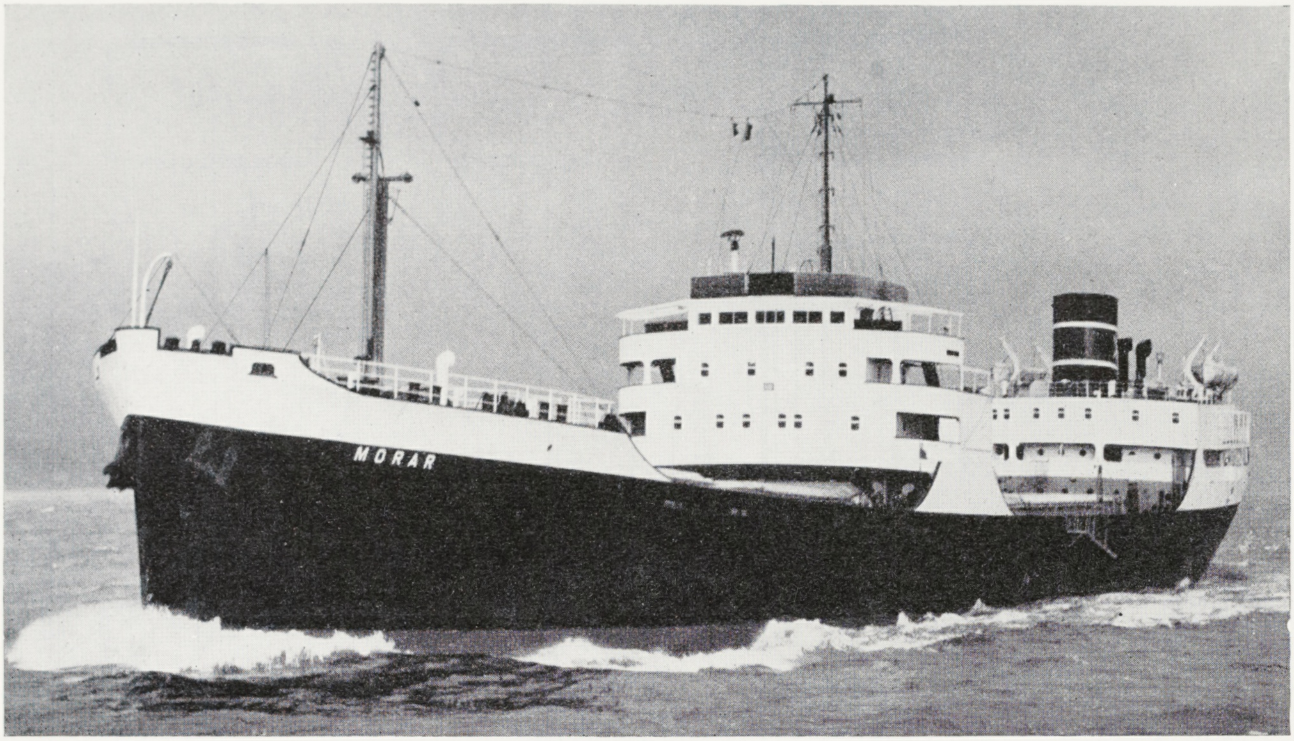



Fig. 10
G.T.V. *Morar*

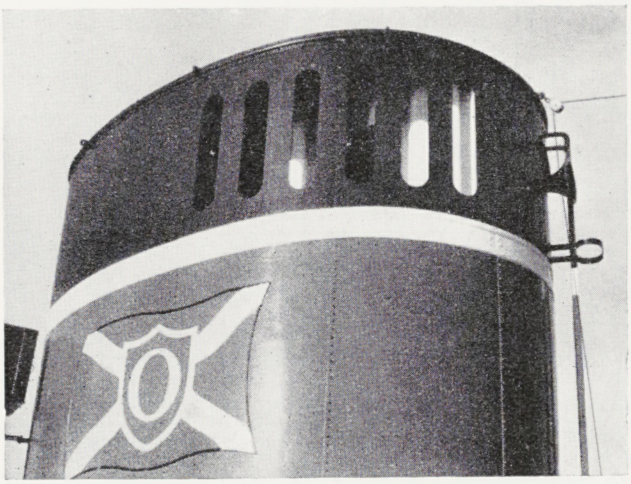


Fig. 11
Combustion air for gas generators ducted from atmosphere through louvres in funnel

**Gas Ducting**

The gas ducting arrangement is shown in Figs. 12a, 12b and 12c, from which it may be seen that a number of expansion bellows pieces are incorporated. These are of stainless steel, fitted with internal sleeves so that the bellows corrugations do not impair the gas flow; they are articulated and fitted with axial ties and flexibly suspended from the deck-head.

A $10\frac{1}{2}$ in. diameter outlet is taken from the gas collector of each gas generator to a 20 in. diameter transverse manifold supplying two 16 in. diameter downcomers leading to two parallel-operating proportioning valves. From each valve a 16 in. diameter to $10\frac{1}{2}$ in. diameter reducing piece leads directly to the ahead nozzle box at the forward end of the gas turbine.

Two similarly-sized reducing pieces lead to the astern nozzle box through side entries in the lower half of the astern turbine at the after end.

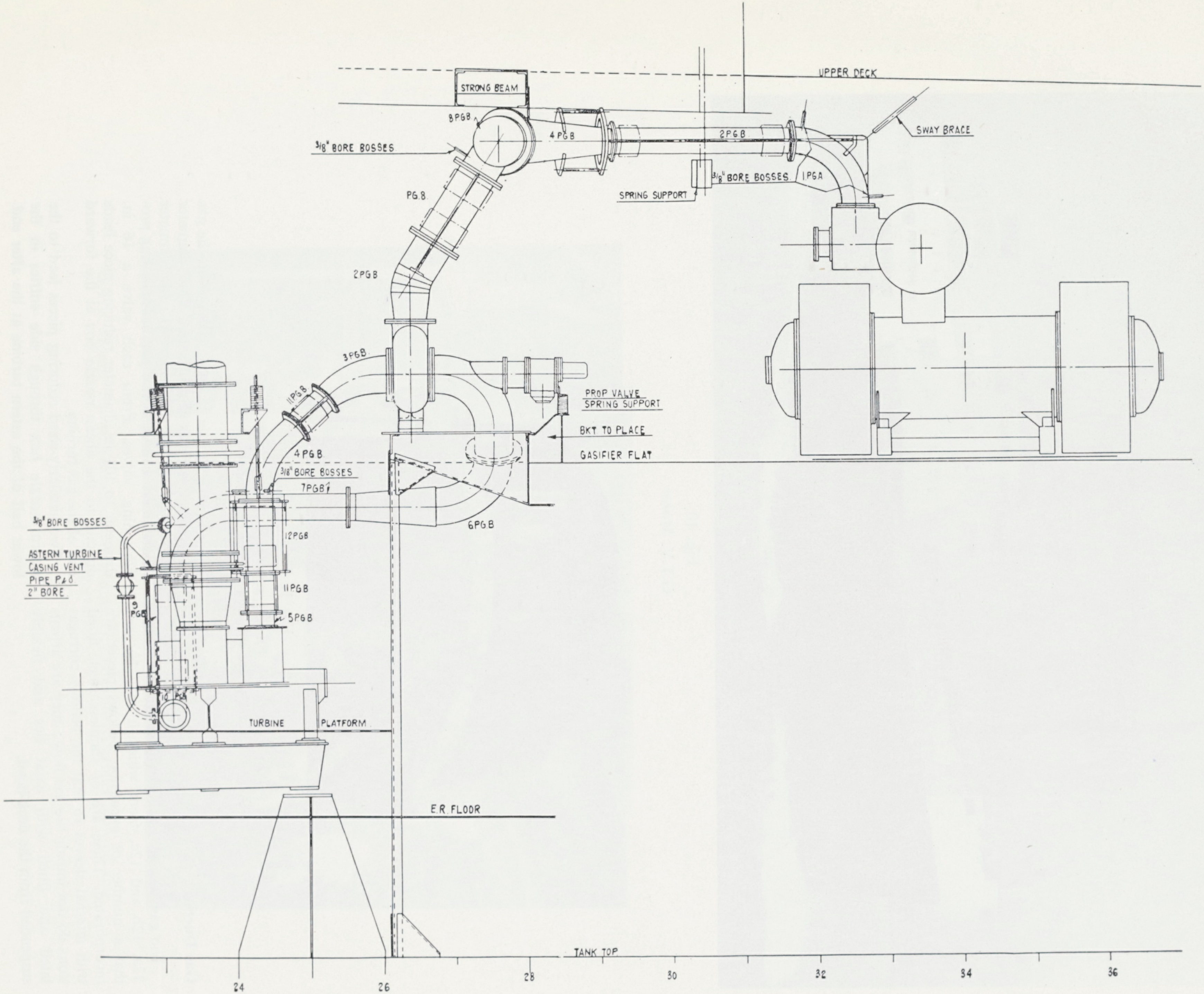



Fig. 12A

G.T.V. *Morar*. Gas ducting arrangement as fitted with Mark I design turbine
Elevation looking to port

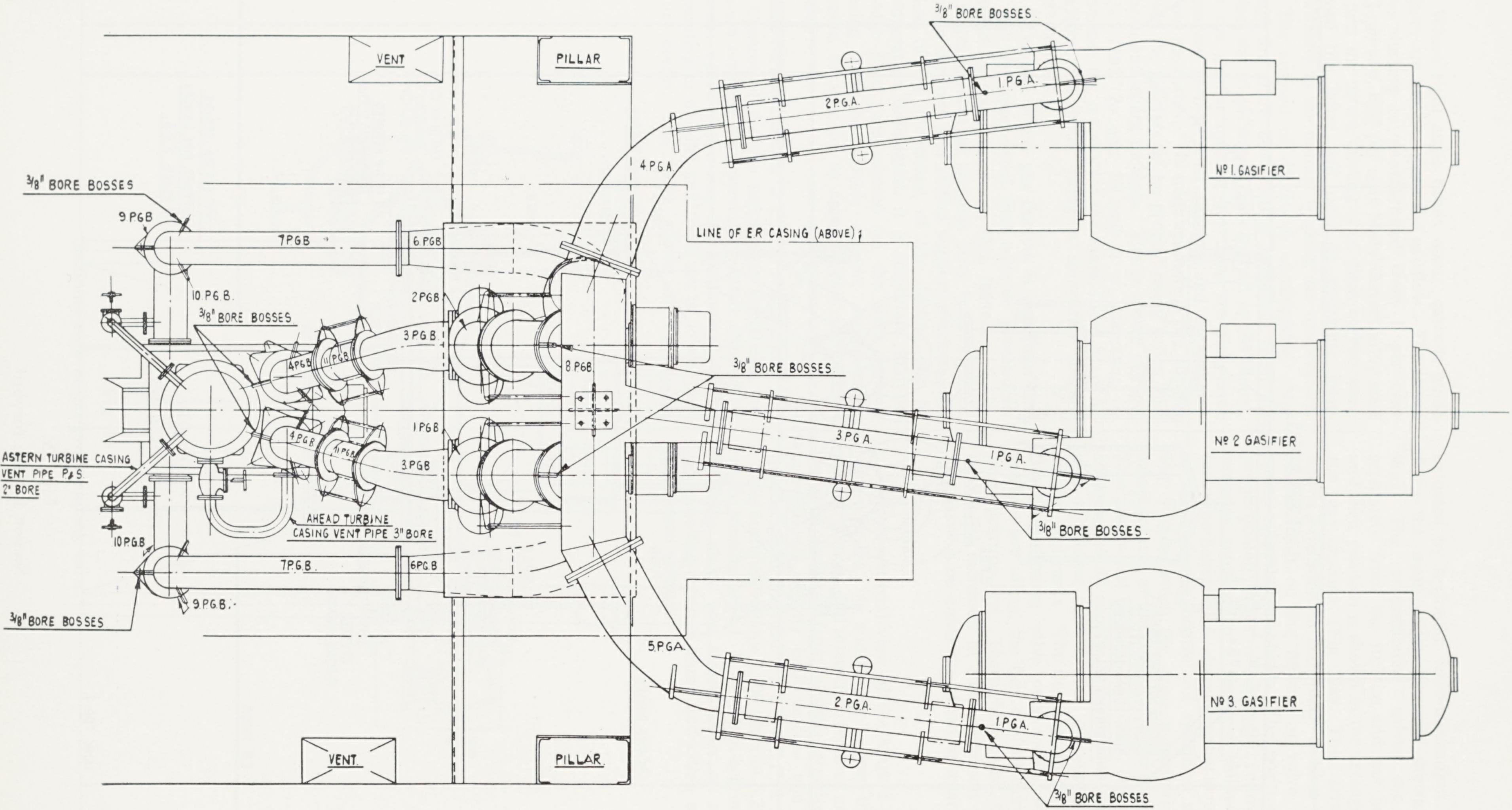



Fig. 12B
Plan View

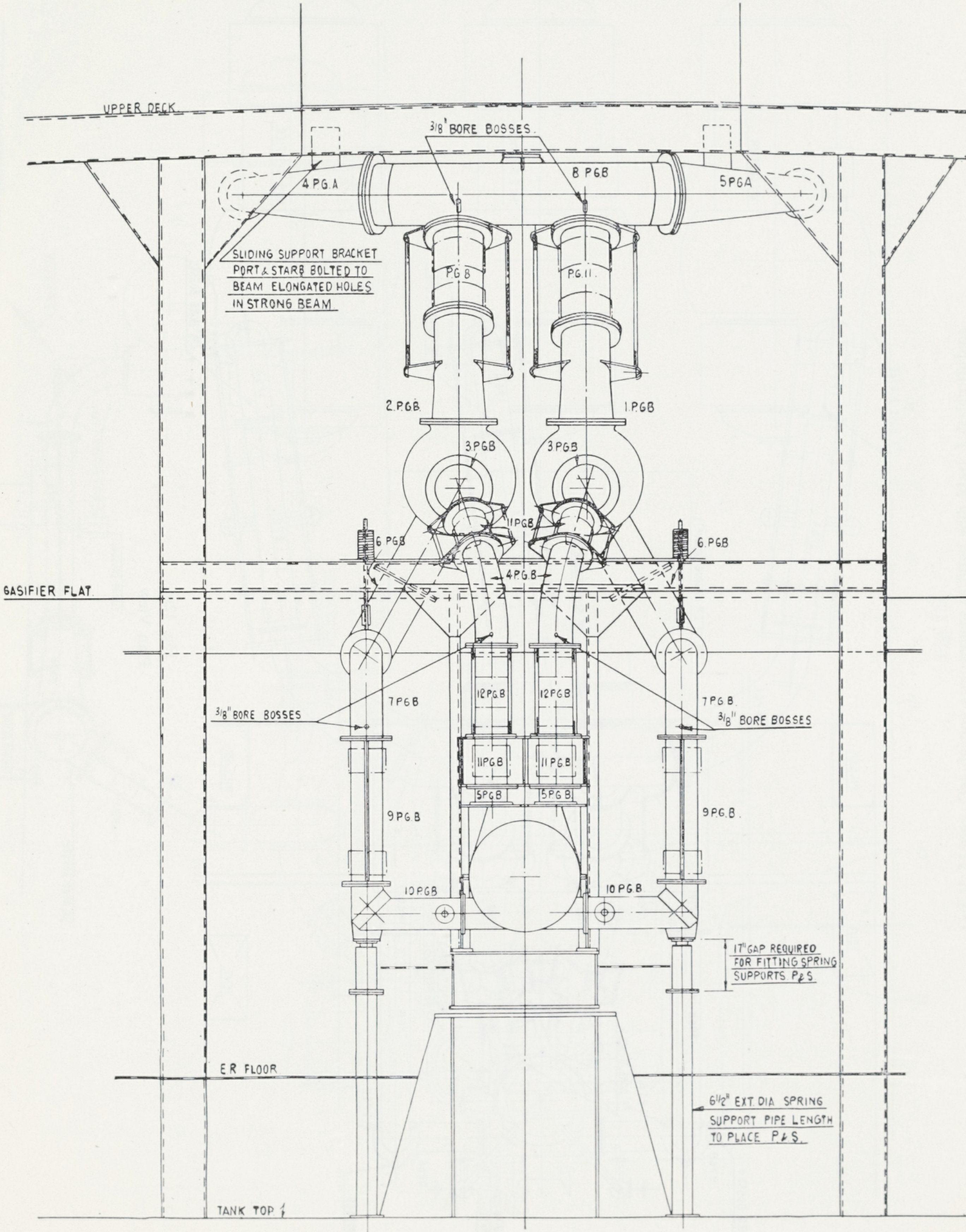



Fig. 12c
Section looking forward

Where right angle bends occur, cascade guide plates are fitted to assist the gas flow. The ahead gas ducting is manufactured from 1 per cent Chromium, half per cent Molybdenum alloy steel whilst the astern ducting is of plain carbon steel, since the latter will only be operating intermittently at the normal working gas temperature.

The amount of ducting is considerable. Not only are there downcomers supplying fresh air from the 30 in. supply fans located in the funnel, to the gasifier intakes, but there are also three separate gasifier relief uptakes and the exhaust from the turbine. In addition there is the ducting from the gasifiers to the proportioning valves and ahead and astern turbines. This is shown in Figs. 12a, 12b, 12c and 16 and it is interesting to compare the layouts for the Mark I and Mark II designs, the latter being a somewhat simpler arrangement.

Flexibility of the gas ducting is important and it will be appreciated that suitable precautions should be taken to ensure this, for example, by an arrangement of stainless steel bellows pieces, spring supports and sliding support brackets. In view of the movement of the ducting due to temperature differential, it is important that no undue loads are exerted on the light turbine casing and the flexible support arrangements should be such as to accommodate such movement.

**Proportioning Valve**

Control of the gas supplied to the ahead and astern turbines is, as previously stated, effected by means of twin two-way "proportioning" valves operating in parallel and these are of Power Jets Ltd. design. The valve shown in Fig. 13 is actuated by hydraulic servo-mechanism operated from the main engine controls shown in Fig. 9(a). The proportioning valves are located separately from the turbine and gas generators and their position is shown in the arrangement of the gas ducting (Fig. 12a). This arrangement allows expansion to take place without imposing undue loads on the turbine or valve which is spring-supported as shown. The position of the proportioning valve is normally controlled by pressure supplied to a sensitive bellows in the servo-mechanism. A diagrammatic arrangement of the hydraulic control oil system is shown in Fig. 9(a) in which the single manœuvring handwheel located at the control console may be seen. This handwheel operates two cams, one of which controls the oil supply to the bellows mechanism and the other controls the oil supply to the gasifier fuel racks. The cams are so profiled that the proportioning valve only moves whilst the gasifiers are idling, the fuel control cam coming into operation first. The turbine speed, therefore, cannot be increased in either direction until the disc valve is on either the ahead or astern seat.

**Gas Turbine**

A cross-sectional view of the Mark I design is shown in Fig. 14a and it may be seen that it has several unusual and interesting features and represents a challenge from aircraft practice to the conventional heavily built turbine met with in marine steam practice.

The turbine develops 2,500 s.h.p. at 5,250 r.p.m. when running ahead. It is a two-bearing design with the ahead and astern rotors on the same shaft, having separate ahead and astern inlets and a common exhaust.

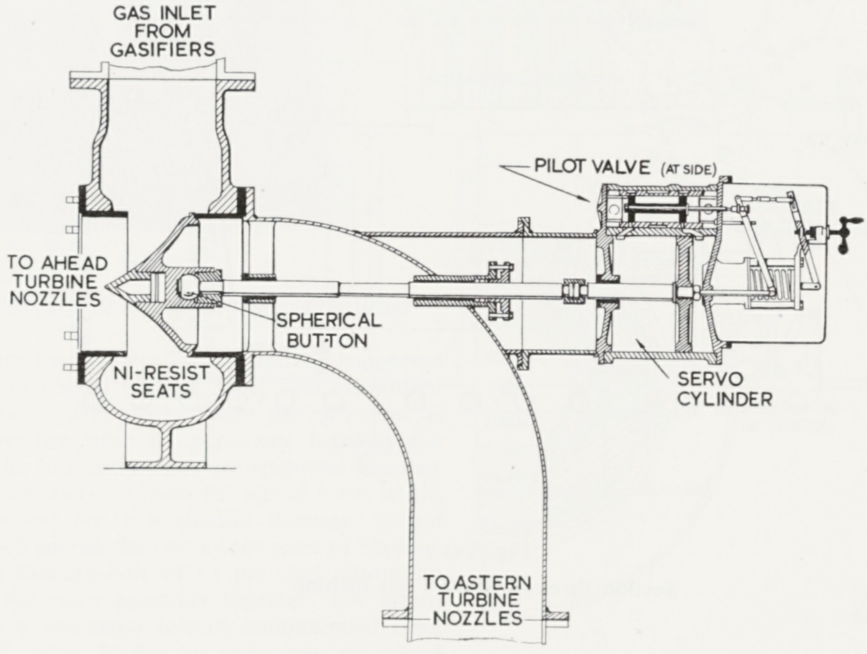



Fig. 13

Sectional view of gas proportioning valve

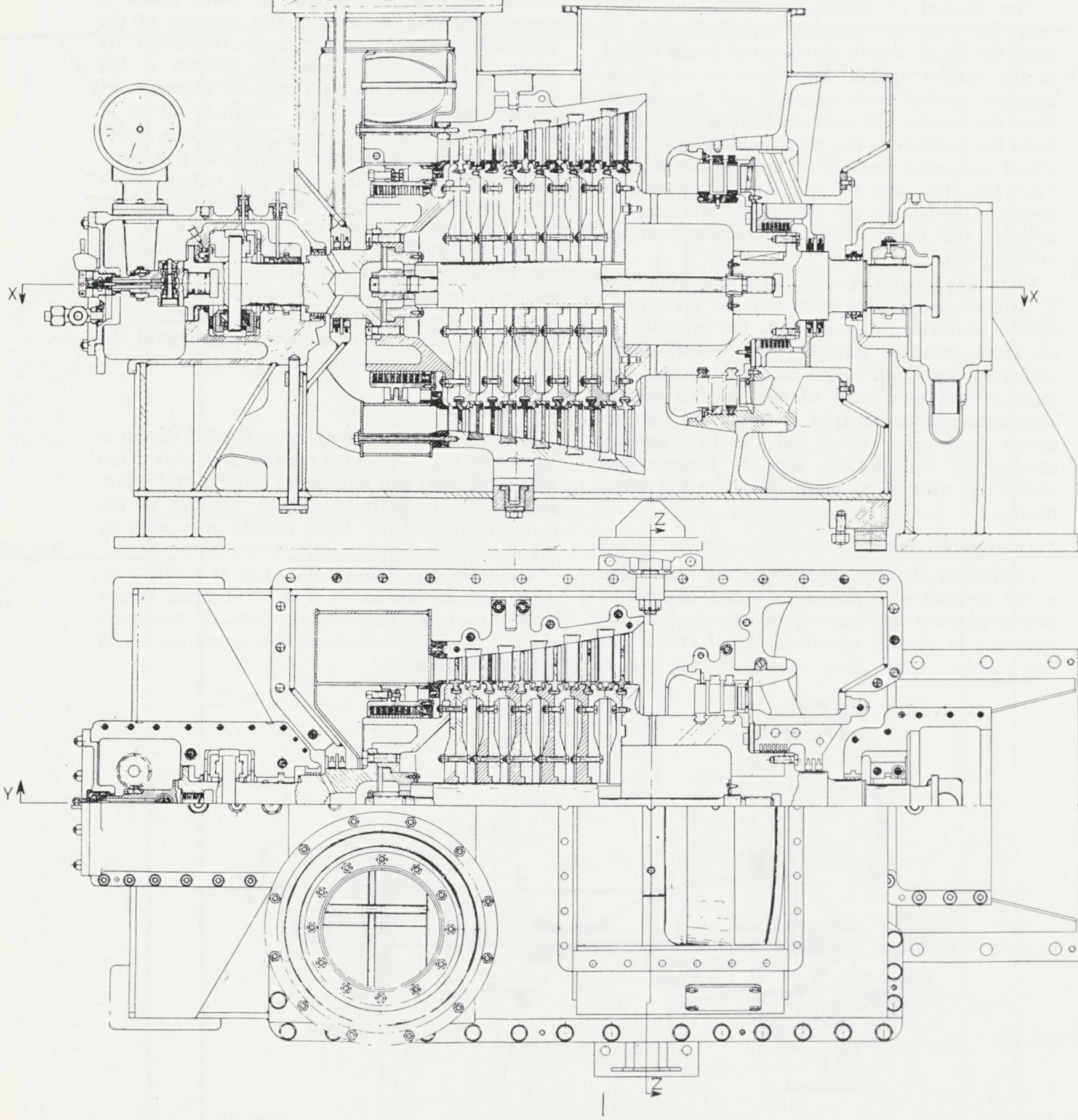



Fig. 14A
Section through Mark I gas turbine

As may be seen from Fig. 14a and 14b the turbine is of a double-casing design. The fabricated outer casing is free to expand axially from its fixed support at the forward end and is carried on sliding feet at the after end where it is guided by a sliding key so as to maintain concentricity of the bearing centres. The forward bearing is attached to the casing and the after bearing is supported independently on the base plate where it is attached to the gearcase. The inner blade-carrying casing is secured by radial keys within the outer casing. The Mark I design has six ahead and two astern stages. The ahead blading is of the reaction type and there are 79 molybdenum-vanadium blades per stage. The blades were produced by the electro-forge upsetting process, in which the material is heated by low voltage high current passed through the stock, the current being confined to that portion of the bar which is to be upset and forged. It is understood that blades produced by this method are widely used in the aircraft gas turbine industry.

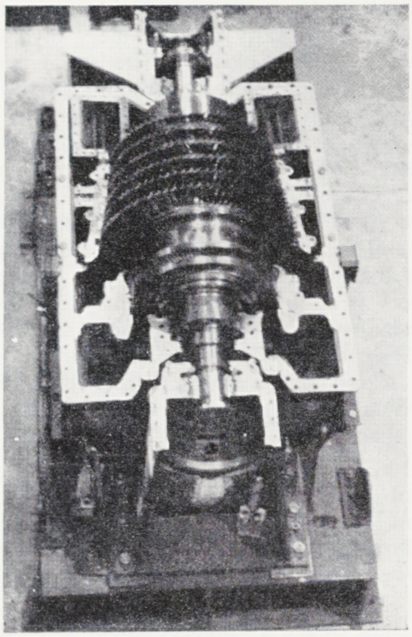


Fig. 14B

G.T.V. *Morar*. Showing turbine casing lifted

The rotor blades have T-roots and are supported in a pair of forged EN 29 (3 per cent chromium molybdenum) steel discs. Each pair of discs is bolted together near its periphery forming the T-root. The successive discs are spigotted together near the periphery to form the ahead rotor which is then bolted on to a smaller diameter forged drum which carries the two astern rows of blading. A central through-bolt of 13 per cent chromium steel ties the rotor assembly together. The astern turbine is a two-stage velocity-compounded type, having 97 rotor blades in each row machined from solid EN 19 (1 per cent CrMo) bar material, the blades having integral shrouds. The ahead nozzles are precision stainless steel castings and there are 76 in each ahead stage. They have integral shrouds at their inner diameters and are supported in circumferential slots machined in the inner casing. This is made in two halves bolted together and secured by a radial key and the arrangement ensures freedom from thermal distortion.

The 42 astern nozzle blades are machined from the solid in EN 24 ($1\frac{1}{2}$ per cent NiCrMo) steel. The 98 second stage astern stator blades are machined from EN 19 (1 per cent CrMo) bar.

The labyrinth packing at the inlet end seals on a forward extension of the rotor end cone and consists of sheet metal rings interleaved between spacers. The double-spacing form of construction allows leak-off from the HP labyrinth to escape directly to the exhaust belt. Similar arrangements are made at the astern end of the turbine. The rotor is supported in two $2\frac{3}{4}$ in. diameter journal bearings and a Michell thrust bearing is arranged at the forward end. A tachometer drive is taken from the forward end of the rotor where the overspeed trip is also located. The ahead gas inlets are in the upper half of the casing and the astern inlets in the lower half. Both admission volute casings allow full-circumference admission for both ahead and astern running.

In order to reduce windage losses in the astern turbine when running ahead, an annular plate deflector is arranged for pneumatic control. This is shown in Fig. 14c and consists of two half rings which, when running ahead, blank off the astern blading and, when running astern, fold back to permit the gases to escape. They are controlled by a pneumatic servo-cylinder located outside the casing and operated from the main control position.

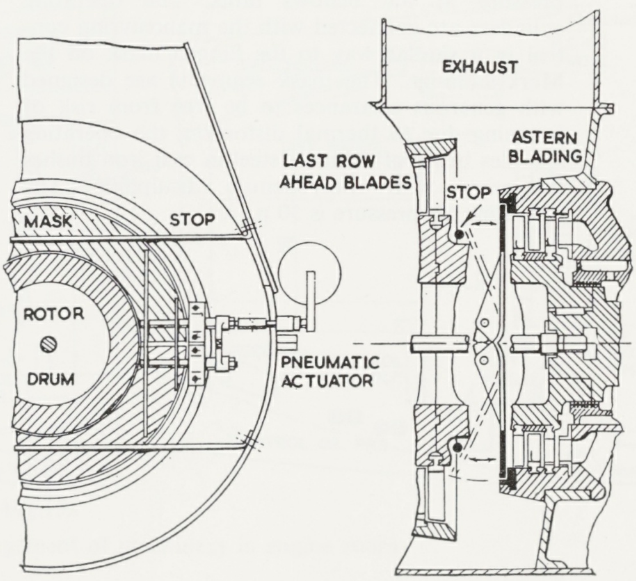



Fig. 14c

Astern turbine masking device to overcome excessive windage loss when running ahead

**Turbine Performance**

The Mark I design has been regarded as a prototype, by means of which experience has been gained showing the way to certain improvements incorporated in the Mark II design to be fitted in the ship.

Test bed results showed a blading efficiency of 86 to 87 per cent for ahead running, but the astern blading windage losses reduced the overall efficiency. The first-stage nozzle area has proved to be larger than required, resulting in the swallowing capacity of the turbine being excessive. The close proximity of the last moving stages of the ahead and astern turbines has also caused a tendency to throttle the exhaust. As a result the overall fuel consumption for the Mark I design is about 0·49 lb. per s.h.p. hour (222·5 gms/s.h.p./hour) which is regarded as unsatisfactory. It is, therefore, interesting to refer to the Mark II design which it is hoped will result in a fuel consumption of about 0·425 lb. per s.h.p. hour (193 gms/s.h.p./hour).

The main modifications consist of the following: —

(1) Increased distance between ahead and astern turbines accompanied by change in design of exhaust guidance arrangements. This will assist in reducing interference of exhaust gas flow from ahead or astern turbines.

(2) One astern stage only, no astern stator blades, smaller nozzles. This will help to reduce windage losses.

(3) Improved astern masking arrangement. These now consist of eight pneumatically operated channel - shaped radially retractable segments which are kept in by springs and forced out by air pressure in the bellows units. The operating cylinders are connected with the manœuvring control in a similar way to the hinged mask on the Mark I design. The mask segments are designed with generous clearances to be free from risk of jamming due to thermal distortion, the operating spindles being of stainless steel in cast iron bushes lubricated with molybdenum disulphide. The operating air pressure is 50 p.s.i.

(4) The pressurised inner volute of the Mark I design is dispensed with and the outer casing becomes the gas container up to the tongue-and-groove joint between the inner and outer casings. The bottom half has a double skin, the inner one retaining the gas pressure and the outer acting purely as a structural connection to the bearing housing.

(5) Handholes located at the high pressure gas inlet end of the ahead turbine casing to give access to the nozzles for cleaning purposes. This modification has been considered desirable to overcome trouble due to partial blocking of the nozzles by deposits thought to result from the use of high viscosity fuel and permits cleaning of the nozzles without the necessity for lifting the turbine upper casing.

(6) The only change in the ducting system was the positioning of the astern inlet pipes which are now in the top half of the turbine case.

**Machinery Arrangement**

Among the advantages of free-piston gas turbine machinery is flexibility of machinery layout, for the gasifiers can be placed where space permits, enabling more room for accommodation, since the engine room casing required is smaller than that necessary for a conventional direct-drive diesel engine. Where space is at a premium the advantage is more pronounced. It was originally intended to fit the *Morar* with a Doxford diesel engine and in this connection it is interesting to observe that the total weight of the free-piston machinery is about 410 tons against 630 tons for the direct drive diesel set, a saving of 220 tons or about 33⅓ per cent. The engine room of the *Morar* is five frame spaces shorter than that of the Doxford-engined ship, representing 12,411 cu. ft. of bale space.

A further advantage of the plant is that in the event of defects or failure of a gasifier, the unit can be stopped and attended to without immobilizing or endangering the vessel, as could happen in the case of a direct drive engine.

The *Morar* has demonstrated that with one gasifier shut down, a speed of about 9 knots was achieved running on the remaining two gasifiers.

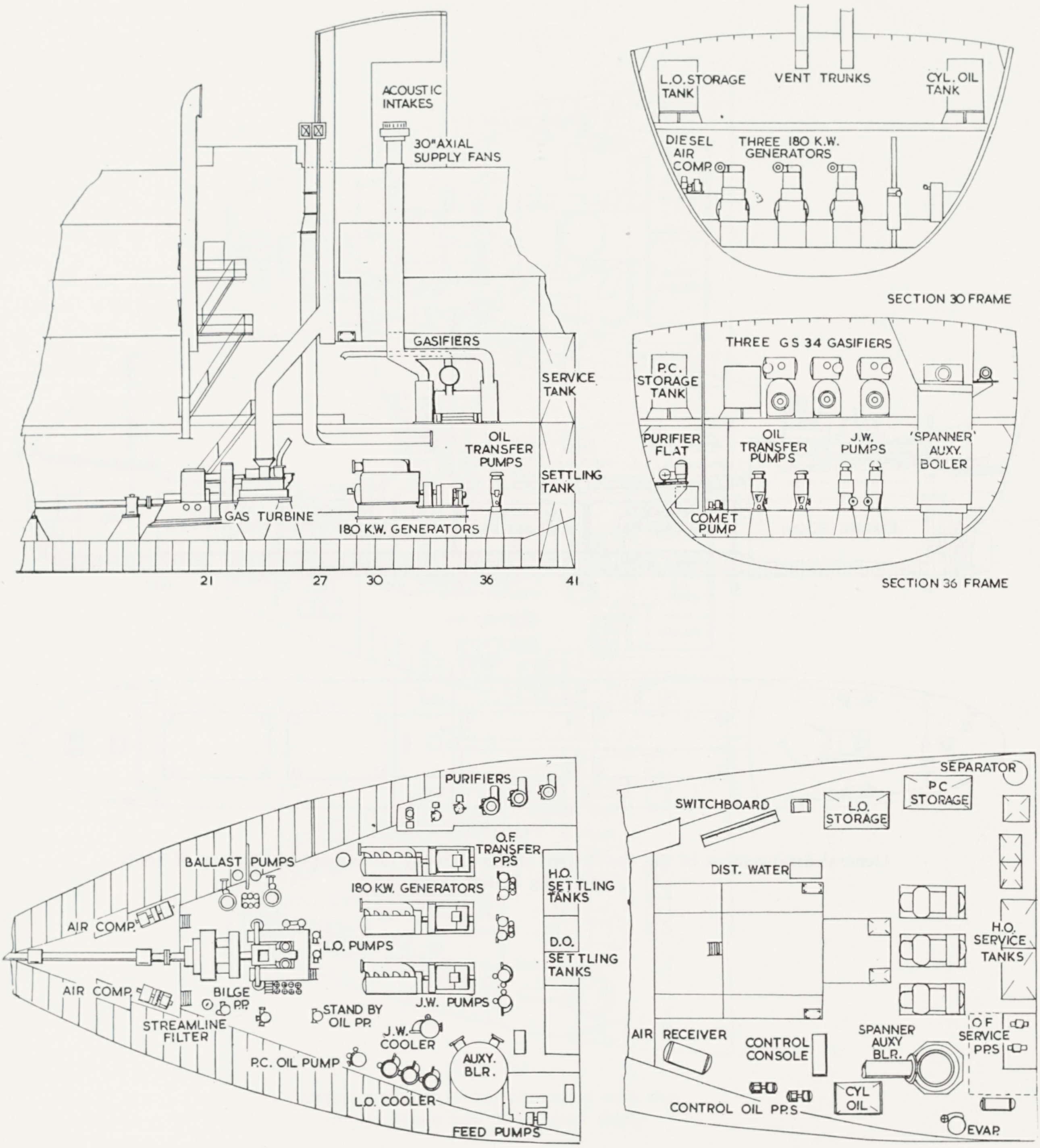



Fig.15A

G.T.V. *Morar*. General arrangement of machinery in engine room

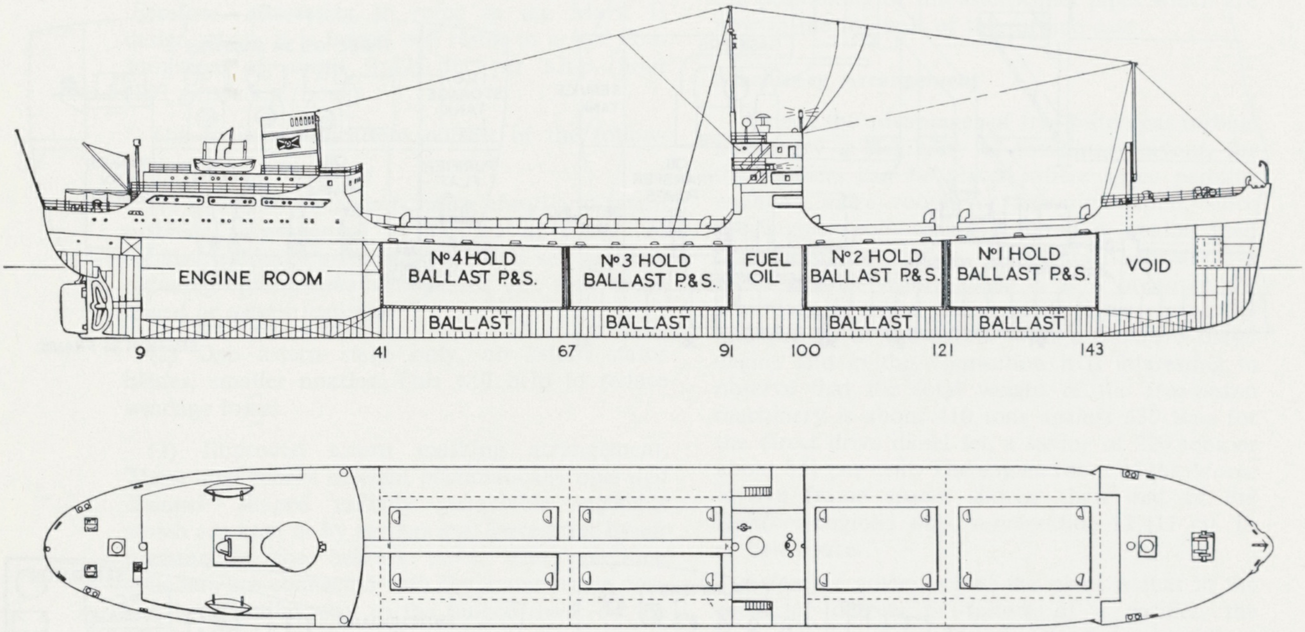



Fig. 15B
General arrangement of the ore carrier *Morar* showing double bottom in way of holds and wing ballast tanks

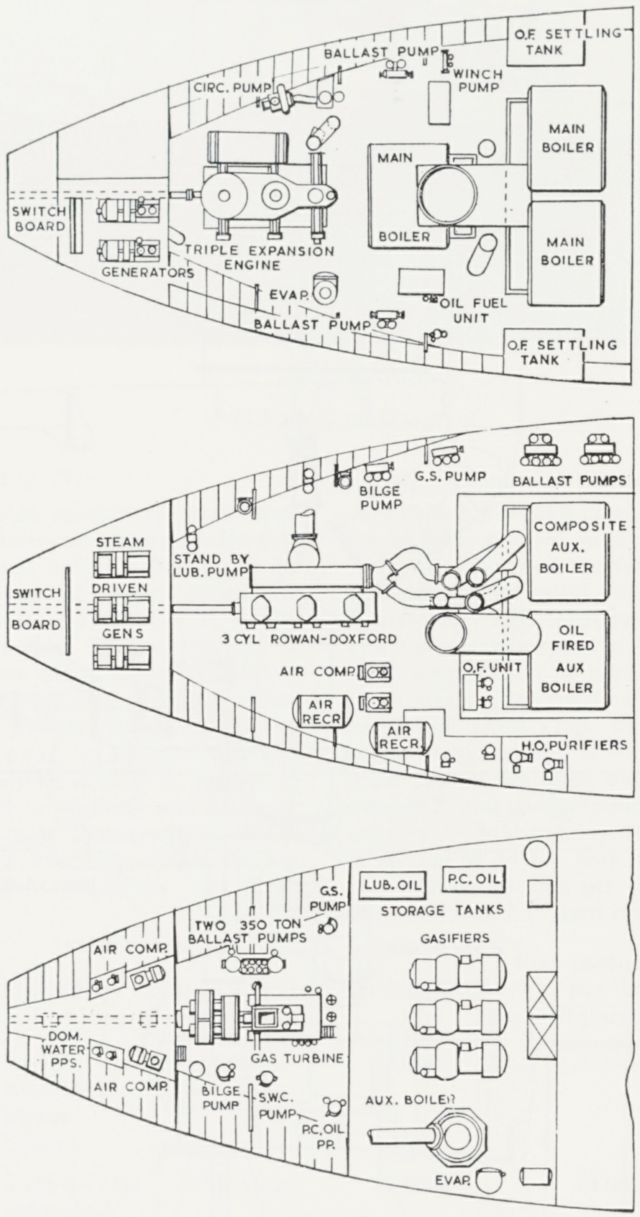



Fig. 15c

Engine room of *Morar* compared with that of her steam and diesel sister ships

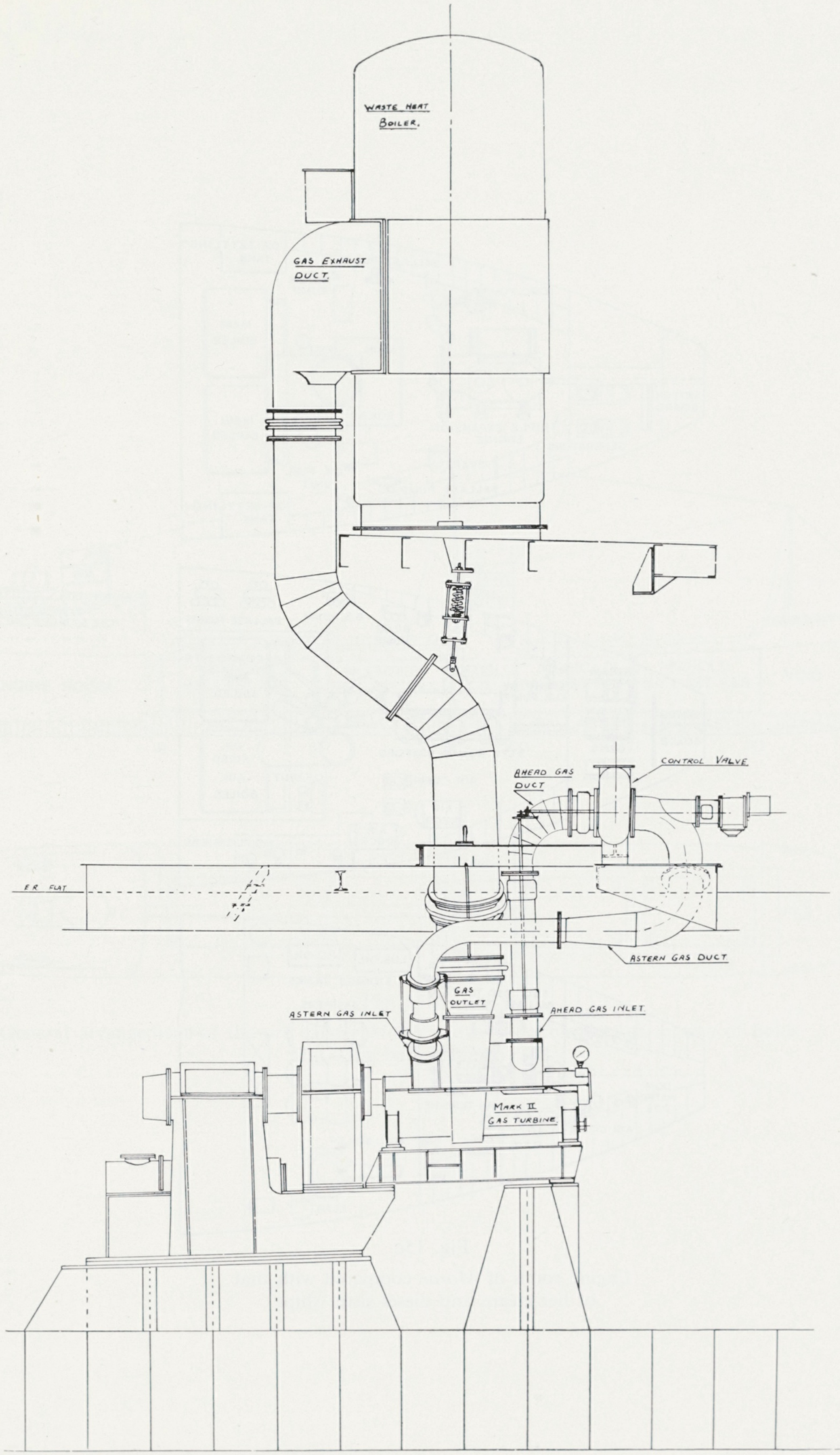



Fig. 16

G.T.V. *Morar*. Gas ducting arrangement as fitted with Mark II design turbine

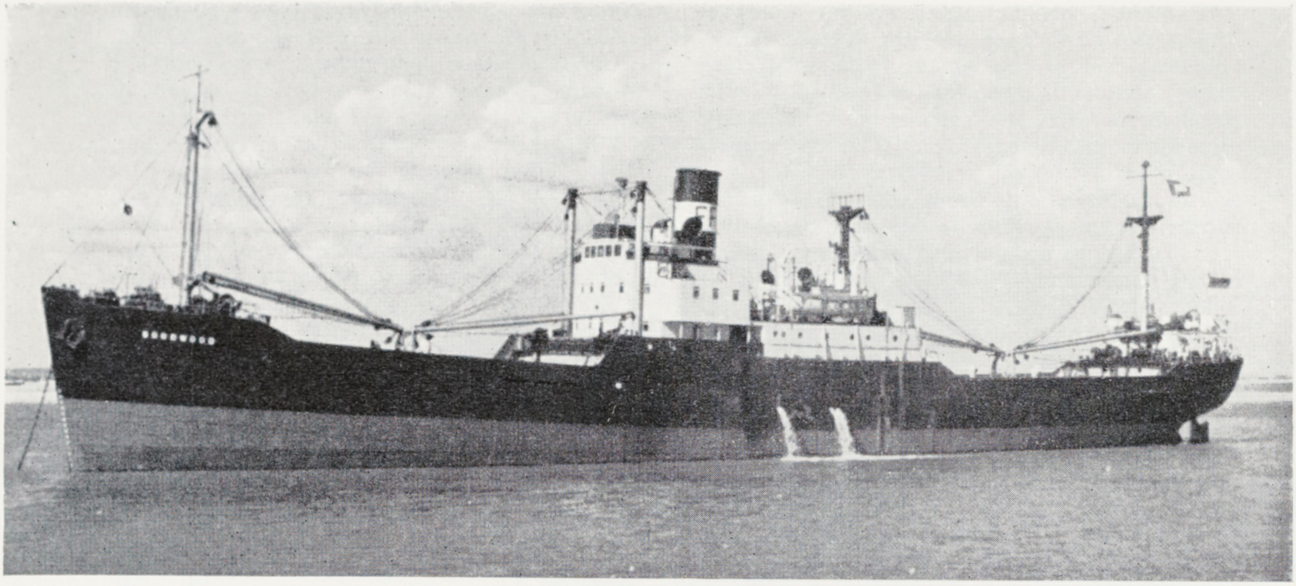


Fig. 17
G.T.V. *Goodwood*

**G.T.V. "Goodwood"** (Fig. 17)

Free-piston gas turbine machinery lends itself well to conversion applications and the above ship is the first vessel classed with the Society to be converted to this type of main propulsion machinery[7]. She was built in 1949 by S. P. Austin & Son Ltd. for Messrs. Wm. France, Fenwick & Co. Ltd. for the deep sea tramp trade. A vessel of 3,485 tons deadweight she was originally fitted with two coal-fired Scotch boilers supplying saturated steam at 220 p.s.i.g. to a triple expansion engine $18\frac{1}{2}$ in. x 29 in. x 52 in. x 39 in. stroke. In 1951 she was converted to oil-firing and for comparative purposes the main characteristics of the *Goodwood* before and after conversion to her present main propulsion machinery are given below:—

| Period | Machinery | Service Power | Service Speed | Fuel consumption per day (all purposes) |
|---|---|---|---|---|
| Before | Triple Expansion Steam Engine | 950 i.h.p. | 10 knots | 10 tons |
| After | 2 GS-34 Gas generators and 1 axial flow gas turbine | 1700 s.h.p. | 12 knots | 10 tons |

The conversion, which was the first in a British-owned vessel and carried out by Messrs. Smith's Dock Co. Ltd., is an example of a ship having a modern hull but fitted with obsolete machinery which could be replaced by plant capable of a higher thermal efficiency. The scheme demonstrates that by exploiting the developments in marine engineering, old tonnage can be made competitive with new construction and can protect the capital invested in a vessel by providing it with an improved performance and extended expectation of useful life. Investigation of the *Goodwood's* hull form revealed that it was suitable for a service speed of 12 knots and that about 1,700 s.h.p. would be required. To meet this, free piston gas turbine machinery having a continuous output of 2,000 s.h.p. was selected so that the actual service rating is 85 per cent of the maximum continuous rated output. At this rating the estimated fuel consumption for the main machinery was 7·7 tons per day. It has in fact been found in service to be 7·6 tons per day. An all-purpose fuel rate of 10 tons per day was expected when due allowance had been made for the ship's steam and electric auxiliary machinery. Based on a ship being at sea 200 days per year, the 20 per cent increase in speed for the same fuel consumption has been stated to represent an increase of 11 per cent in earning power. To this may be added any earnings due to the 50 tons increase in deadweight made available by a similar decrease in the

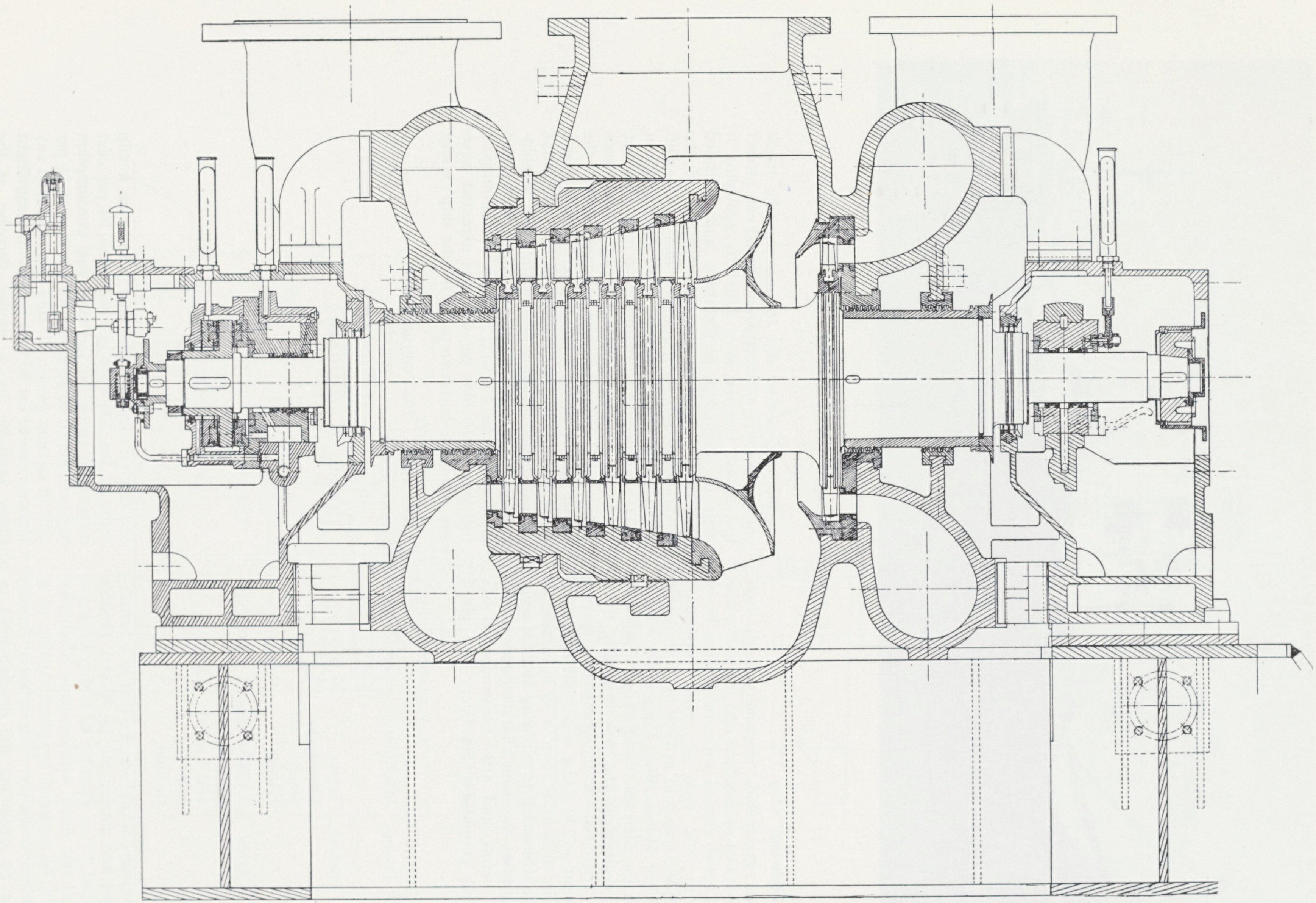


Fig. 18

G.T.V. *Goodwood*. Cross-section of reversible turbine, showing toroidal baffle in front of the astern blading

machinery weight, together with any charter rate increase resulting from the higher service speed.

These figures illustrate the margin in favour of the free piston engine system as a replacement for existing steam plant. The improved power-weight ratio and power-bulk ratio of the system enables the higher-powered installation to be accommodated in an existing engine room.

The new propulsion system in the *Goodwood* consists of two Smith-Pescara G.S.34 type free-piston gasifiers which supply power gas to a reversing expansion turbine (Fig. 18) supplied by Messrs. Alsthom of Belfort in France and having six ahead stages and one astern stage carried on a single gashed rotor.

In contrast to the *Morar* there is no movable mask between the ahead and astern outlets. The static internal baffling fitted to the *Goodwood* has been successful in preventing overheating and loss of power by windage. Views of the turbine and starboard gasifier are shown in Figs. 19 and 20 and a general arrangement of the engine room after conversion is shown in Fig. 21.

As may be seen from the latter the gasifiers are arranged on each side of the turbine and at the same engine room floor plate level. The gas ducts are led so that each gasifier supplies one half section of the first stage admission nozzles. This enables the full designed gas delivery pressure to be maintained when only one gasifier is running without the need to shut down any nozzle groups. The ahead/astern manœuvring valves are mounted on top of the turbine casing and, as in the case of the *Morar*, permit the gas flow to be proportioned between the ahead and astern turbines at the same time so that a balance giving zero torque at the turbine shaft coupling can be attained.

The machinery is controlled in a similar way to that of the *Morar*. Operation of the single hand-wheel at the control console turns a shaft fitted with two cams each controlling a separate pressure-regulating valve, both supplied with oil at constant pressure from the piston-cooling oil system.

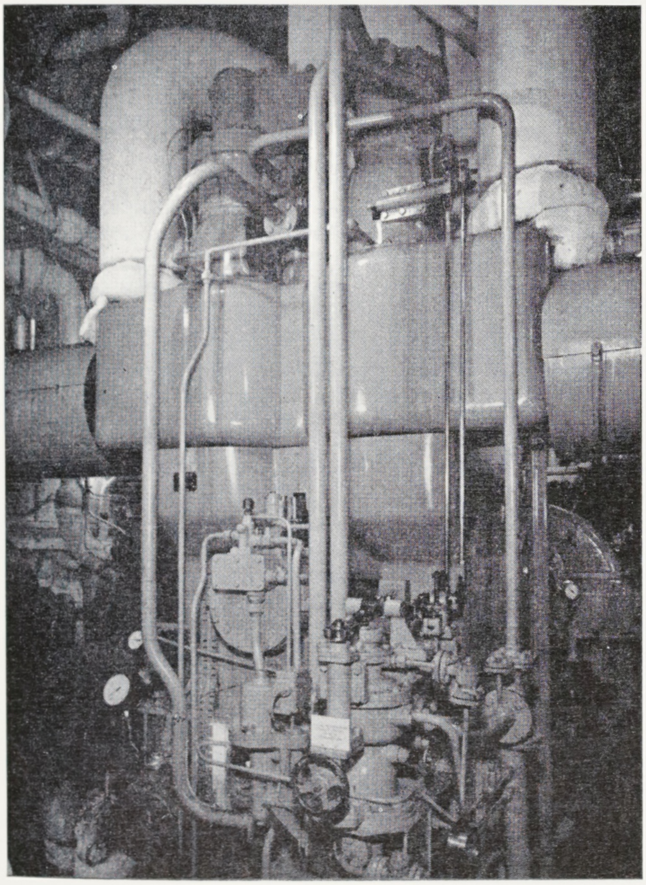


Fig. 19

Forward end of gas turbine with proportioning valves above

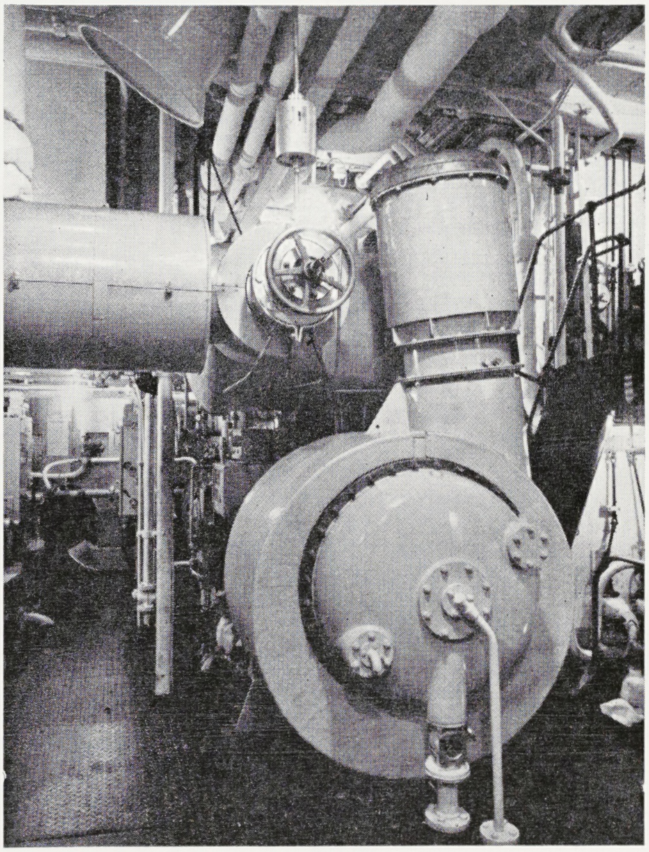


Fig. 20

Starboard gasifier. The air intake chamber contains a free running Aerofoil fan

Similar safety devices to those fitted on the *Morar* are provided. These include an over-speed governor for the turbine and over-stroke trips for the gasifiers. Operation of any of these will stop the plant by operating relief valves on the gasifier fuel pump delivery chambers. The pump spills its fuel before the injector opening pressure is reached and the gasifiers are stopped in one full stroke. The relief valves are of the diaphragm type and are normally loaded hydraulically with oil at constant pressure, but when the trips operate, this

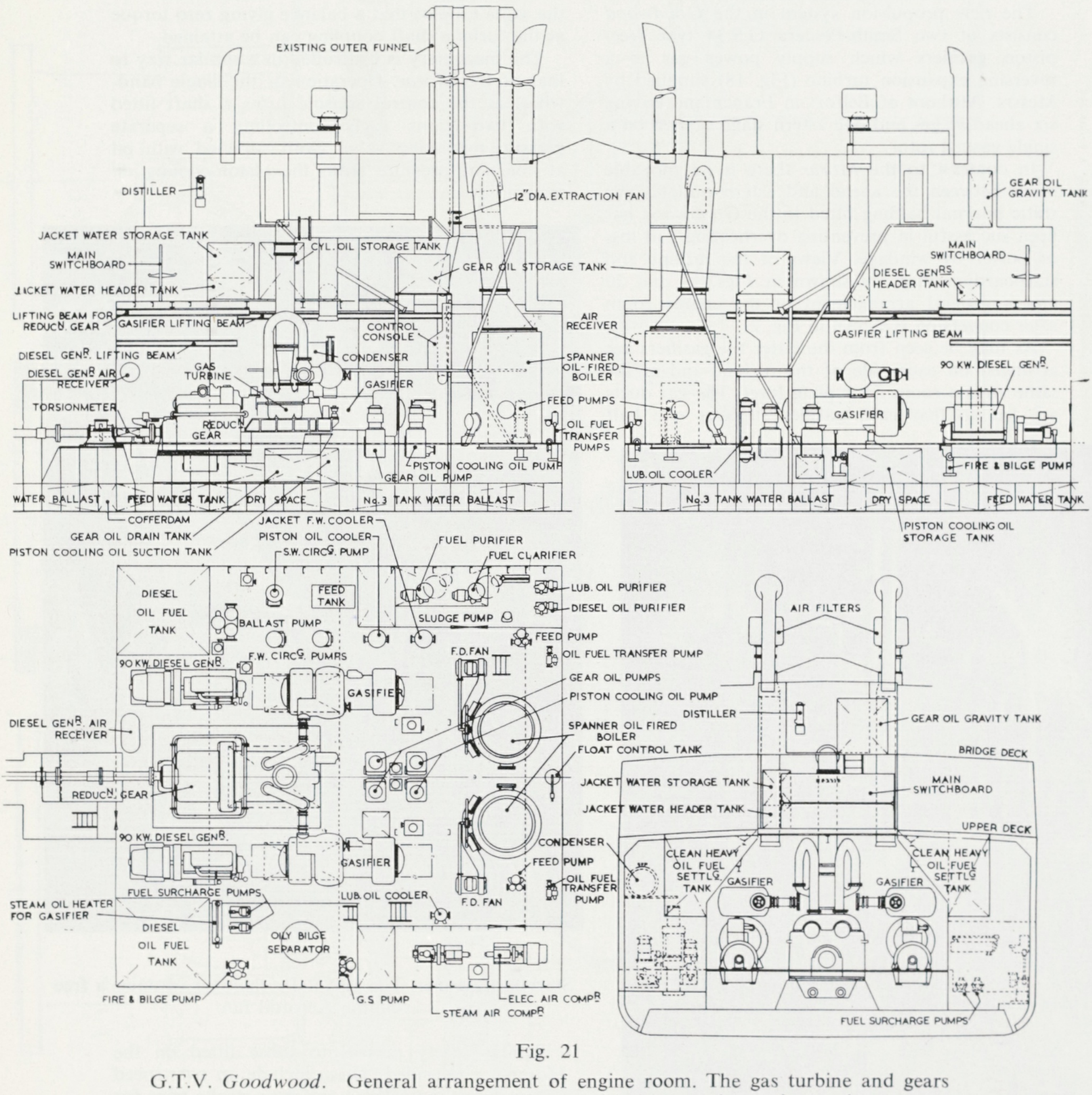



Fig. 21

G.T.V. *Goodwood.* General arrangement of engine room. The gas turbine and gears occupy part of space formerly taken up by steam reciprocating engine

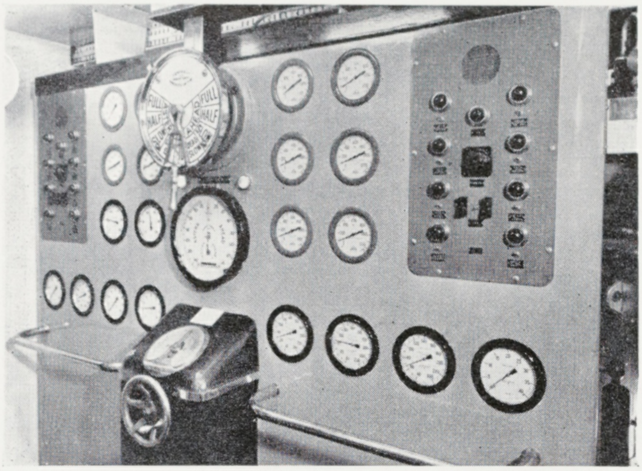


Fig. 22
G.T.V. *Goodwood.* Main engine control panel.

oil is shut off and the pipe to the diaphragm valve is vented to atmosphere. With no pressure on the diaphragm the pump spills its fuel.

Hand-operated valves are arranged in a similar manner to the trips, so that the plant can be shut down instantaneously in emergency from the control station or from the turbine. An Aspinall type of governor is fitted to the gearbox and is arranged to prevent racing in a seaway. It operates by reducing the control oil pressure to the proportioning valve servo-unit if the maximum speed is exceeded, with the result that the manœuvring valve moves slightly and some gas is admitted to the astern turbine thus slowing down the shaft. A low-oil-pressure alarm is mounted on the turbine.

The *Goodwood* conversion demonstrates the advantages of the free-piston engine system as applied to the rejuvenation of existing steam tonnage, the geared drive permitting a shaft speed to be chosen, which enables the existing shafting to be used.

### G.T.V. "Robert W. Vinke"

This vessel is a whale catcher built by Messrs. Scheepswerf De Hoog for Messrs. Nederlandsche Maatschappij voor de Walvisvaart. Three G.S.34 type free-piston gas generators manufactured under licence by Messrs Amsterdamsche Droogdok Mij. are fitted supplying one 3,000 s.h.p. gas turbine of the Mark II Power Jets design referred to earlier in the paper. The hydraulic control system is to be similar to that fitted in the G.T.V. *Morar*.

### G.T.V. "Rembrandt"

This vessel is a cargo ship of 12,500 tons deadweight built and engined by Smith's Dock Co. Ltd. and is of special interest, since a controllable-pitch propeller of the Stone-Kamewa type (Figs. 23a and 23b), the largest yet manufactured in Britain being 16 ft. in diameter and weighing 38 tons[8], is fitted in conjunction with the free-piston gas turbine machinery, the first time that such a combination has been installed in a vessel classed with the Society. Five G.S.34 type gasifiers are fitted, four of which are required to produce the full power of about 4,000 s.h.p. developed in the six-stage non-reversing gas turbine of Associated Electrical Industries Ltd. drum type design running at 6,800 r.p.m. Double reduction gearing reduces this to 120 r.p.m. at the propeller. In an installation of this type the controllable-pitch propeller offers worthwhile advantages, since its adoption avoids the necessity of an astern turbine thus eliminating windage and astern losses.

This vessel, the largest and most powerful free-piston engined ship yet built in the U.K., ran initial trials in July, 1960[9]. In the ballast condition a speed of 14·58 knots was obtained with a specific fuel consumption of 0·428 lb./s.h.p./hour (194·5 gms/s.h.p./hour) when developing 3,870 s.h.p. The designed sea speed when fully loaded is 13 knots in average weather.

The weight of the main machinery installation is as follows:—

| | Tons |
|---|---|
| 5 G.S.34 type gasifiers with recirculation arrangements ... ... ... ... | 41·0 |
| 1 gas turbine with lagging and cleading | 6·0 |
| 1 double reduction gearbox with thrust block ... ... ... ... ... | 30·15 |
| 1 set gas piping between gasifiers and turbine complete with lagging ... | 3·5 |
| 1 control console with instruments ... | 1·15 |
| 1 set blow-off piping complete with lagging ... ... ... ... ... | 1·3 |
| Total weight of main machinery ... | 83·1 |

The total machinery weight is 420 tons and this includes main and auxiliary machinery, pipes and fittings, oil and water systems, tanks, sterngear, floors and gratings, funnel and vents, spares and stores.

It has been reported that when idling the gasifiers develop only 20 s.h.p. each with the recirculation arrangements in use and as a result it is possible to manœuvre in restricted waters with great precision.

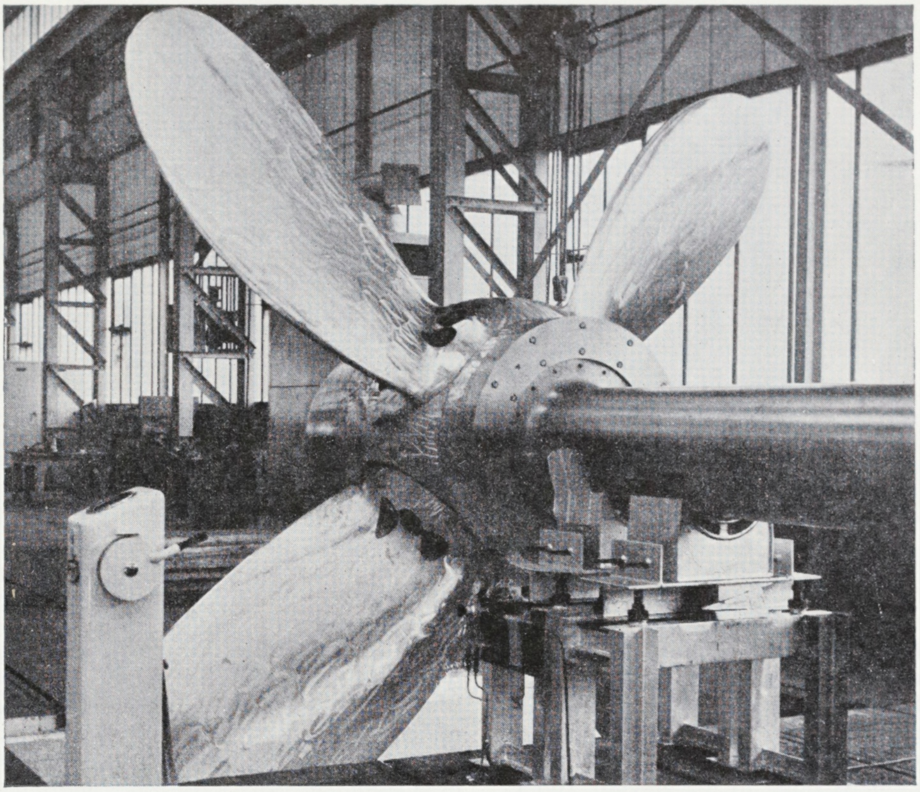


Fig. 23A

G.T.V. *Rembrandt*. The Stone-Kamewa controllable pitch propeller and bridge/engine room control unit

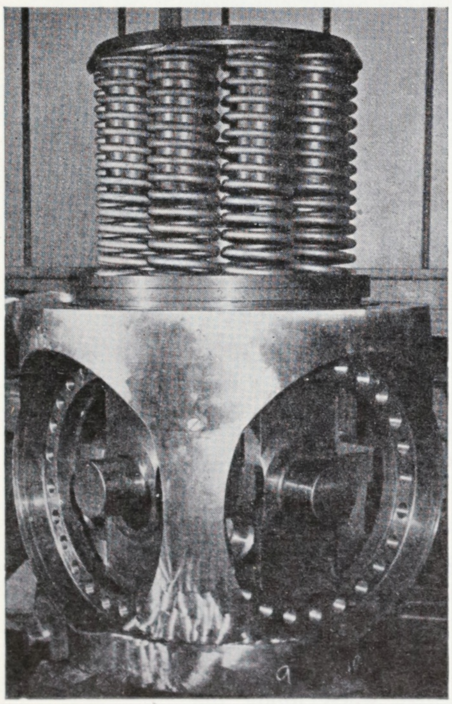


Fig. 23B

G.T.V. *Rembrandt*. The hub body showing the safety springs and hub mechanism

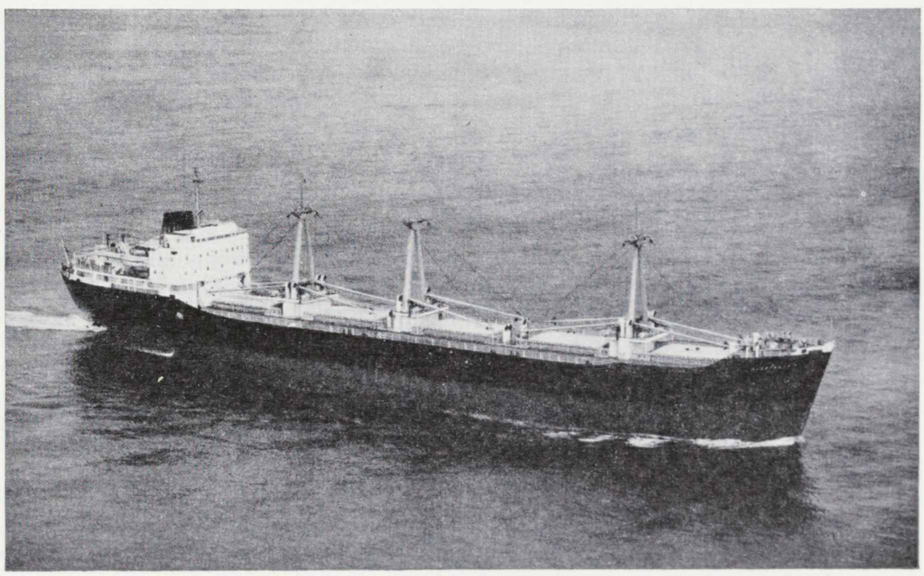


Fig. 24

G.T.V. *Rembrandt*

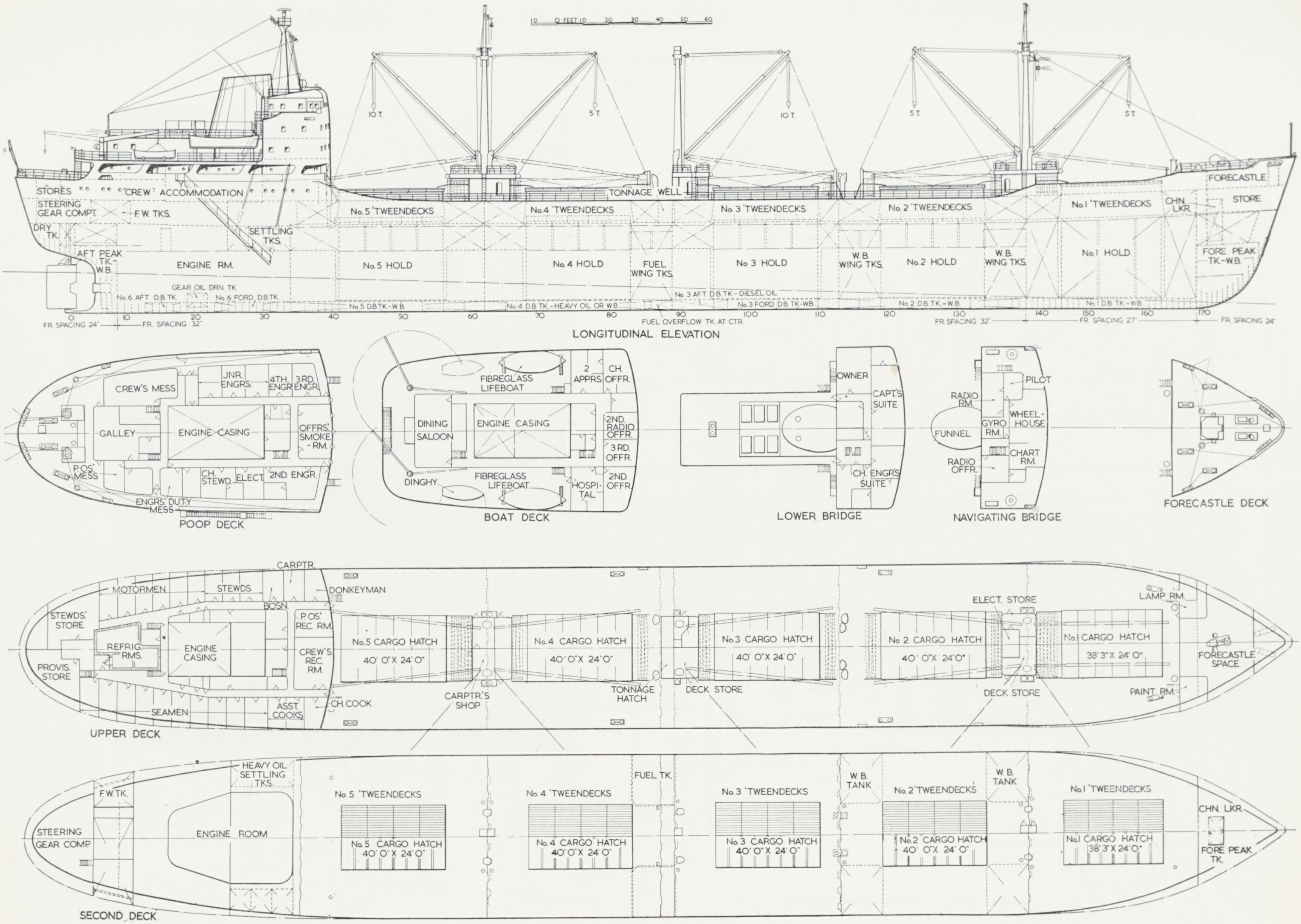



Fig. 25

G.T.V. *Rembrandt*. General arrangement

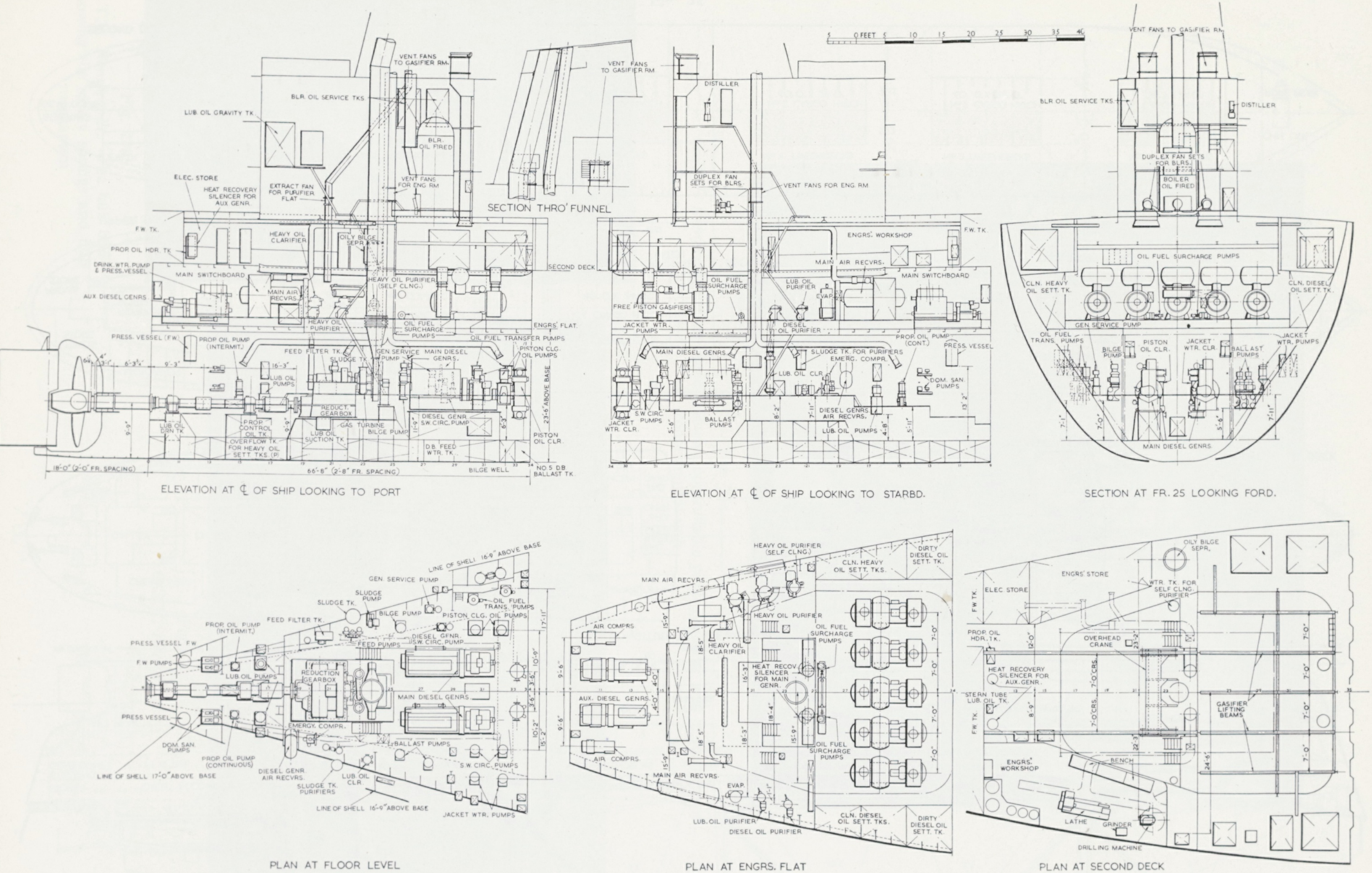



Fig. 26

G.T.V. *Rembrandt*. Machinery arrangement

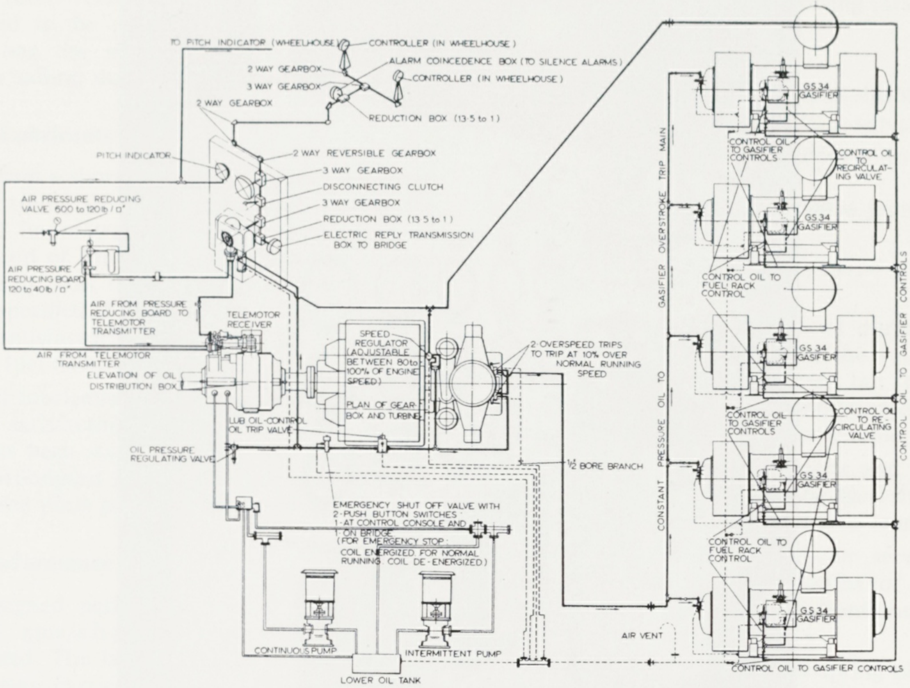



Fig. 27

G.T.V. *Rembrandt*. Diagrammatic arrangement of bridge and engine room controls for the propeller and gasifiers.

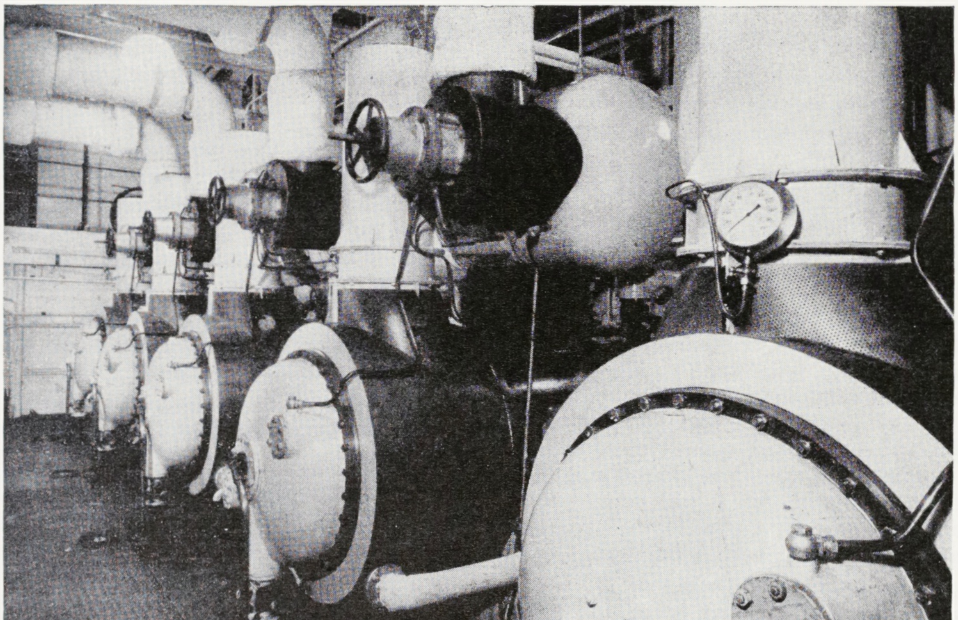


Fig. 28

G.T.V. *Rembrandt*. The five free-piston gasifiers are grouped in a separate compartment

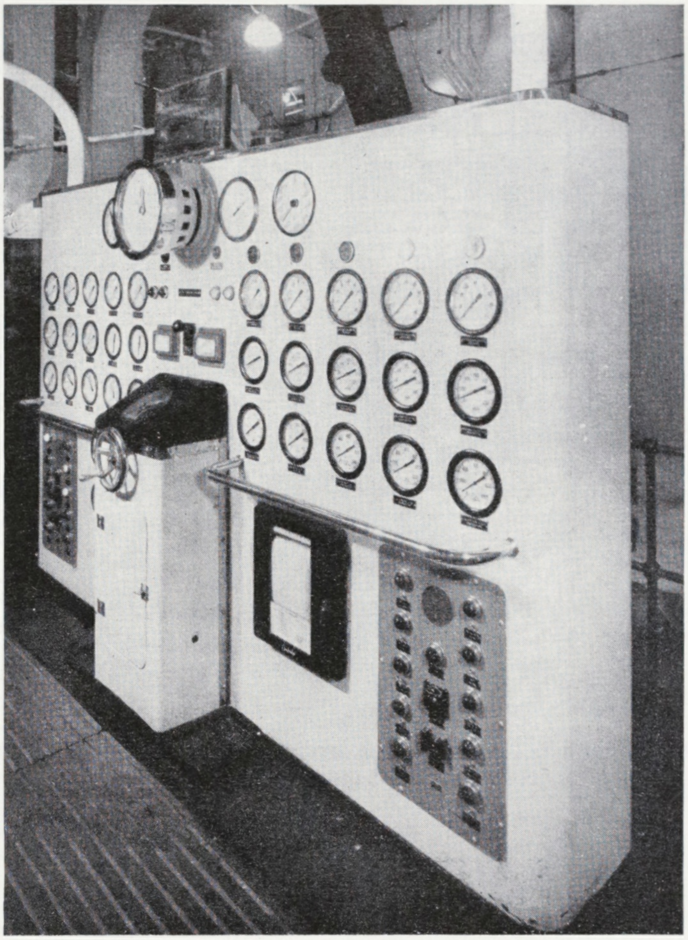


Fig. 29
G.T.V. *Rembrandt*. Main engine control console

**Operational experience**

In connection with service experience it is considered of interest to include a report[5] on the first eight months of operation of the G.T.V. *Goodwood*.

The ship sailed from the Tees in April, 1959, and a total running time of just over 3,000 hours for the turbine and each of the two gasifiers has now been logged.

At the time of conversion, it was decided by the owners that although *Goodwood* was the first British ship to be converted to this type of propulsion, no special steps would be taken to exclude her from her normal trades. It will be seen from the records of voyages completed since April, 1959, that this policy has been maintained:—

Voyage 1—Ghent to Philadelphia.

Voyage 2—Prince Edward Island to Velsen (Holland).

Voyage 3—Archangel to Vilvorde (Belgium).

Voyage 4—Kara Sea to London.

Voyage 5—Kara Sea to Hull and Grimsby.

Voyage 6—Archangel to Vilvorde.

To complete this programme, the vessel has encountered severe North Atlantic weather, forced ice in the Kara Sea, manœuvred up and down the canals to Vilvorde on two occasions without damage, and encountered severe freezing on her last voyage to Archangel.

It is of interest to note, and speaks well of her manœuvring abilities, that she is one of the largest ships to have reached Vilvorde.

At all times the engineers have had complete confidence in the machinery.

Due to the present shipping depression, the owners say it is difficult to comment on the financial results of the first eight months' operations, except that if the conversion had not been done, the vessel would have undoubtedly been laid up during this period, while in fact she has contributed towards her depreciation. It was not expected that any real profit margin would be obtained until the machinery was burning residual fuel. In this connection, the last voyage, Grimsby–Archangel–Vilvorde, was carried out using high viscosity fuel of 1000 secs. Redwood I at 100° F.

Engine room reliability and performance have been stated to be most satisfactory and on no occasion has the ship been without power or delayed in sailing due to engine trouble.

**Fuel and Lubricants**

Apart from a short run on a 2,000 sec. Redwood I fuel on trials, all gasifier operation during the first 2,500 hours was on marine diesel fuel, as from the end of May, 1959, until October of that year the ship was under charter, for which this fuel was specified. Since then the *Goodwood* has operated satisfactorily for over 500 hours on a 1,000 sec. fuel (Red. I).

Mobiloil lubricants have been used throughout, and very satisfactory lubrication of the gasifier engines has been stated to have been achieved so far with Mobilgard Marine 593 oil, at an oil flow rate of three pints per hour per gasifier.

**Engine Performance**

The designed performance of 0·42 lb./s.h.p./hour (191 gms/s.h.p./hour) at 1,700 s.h.p. has been realised. The last voyage of some 200 hours duration was carried out on 1,000 sec. fuel at 1,700 s.h.p., at an average specific fuel consumption for the whole voyage of 0·418 lb./s.h.p./hour.

**Gasifiers**

The gasifiers were built by Smith's Dock Co. Ltd. under licence from Messrs. Alan Muntz & Co. Ltd. and, as previously stated, are of S.I.G.M.A./S.E.M.E. type G.S.34 design.

During the first six months of operation on marine diesel fuel, a gasifier stopped while at sea on three occasions, but in all cases the other gasifier was unaffected and continued running.

These stops were due to: —

| | Time out of service |
|---|---|
| Manœuvring piston fracture ... | 30 hours |
| Fuel pump return spring failure | 16 hours |
| Fuel pump accumulator plunger seizure ... ... ... ... | 3 hours |

The manœuvring rod failure was the most serious, and no attempt was made to repair the gasifier until the ship was in port 30 hours later. Damage was found to be very slight, but later the piston synchronizing linkage was removed, as the link bush had been elongated.

The fuel pump return spring failure occurred shortly after the manœuvring piston failure. Consequently, although the trouble was rapidly diagnosed, it was decided to check the linkage gear at the same time, prolonging the period for which the gasifier was out of service. A second fuel pump return spring failure occurred within the last 500 hours and was made good in under an hour.

In addition to the above stops, a gasifier was shut down while in open sea on ten occasions to investigate and repair the following faults: —

| | Time out of service |
|---|---|
| Remove insecure internal heat shield | 3 hours |
| Repair leaking cushion release valve | 12 hours |
| HP fuel line joint leaks (6 occasions) | 12 hours (total) |
| Renew damaged suction valve joint washer ... ... ... ... | 1 hour |
| Replace cracked water inlet pipe on headplates ... ... ... | 8 hours |

Some trouble was experienced during the first voyage from water leaks from the valve pockets in the compressor headplates, but these were replaced by headplates of a modified design after this voyage, and have given no trouble since.

Inspection of the moving parts and interior of the engine after 2,500 hours has shown both gasifiers to be very clean and free from deposits.

A complete list of all new or serviced parts fitted during the first six months of operation, including those parts already mentioned is given below: —

- 4 sets of fuel pump buffer spring plates
- 1 manœuvring piston and coupling
- 1 set of piston synchronising linkage bushes
- 1 fuel pump return spring
- 4 compressor cylinder headplates (scheduled before delivery on account of design change)
- 2 sets fuel injector nozzles
- 1 cushion release valve spring
- 2 compressor delivery valves
- 1 compressor suction valve, joint washer and clamp plate
- 2 piston-cooling oil gland rings
- 1 compressor headplate inlet water pipe
- 3 fuel pump accumulator plunger assemblies
- 1 fuel pump metering plunger assembly

Apart from the compressor headplates, which were scheduled for changing due to a design alteration introduced to overcome the problem of leakage, the total value of spares consumed as listed above was approximately £180.

**Gasifier wear figures**

Measurements taken after 2,500 hours of operation indicate that the maximum rate of wear on the engine cylinder diameter is about ·001in./1,000 hours for the scavenge liner, and under ·002 in./1,000 hours for the exhaust liner.

Maximum radial wear per 1,000 hours for the top three piston rings, ignoring wear at the ring horns, is under ·005 in. for both top rings, under ·001 in. (scavenge) and ·002 in. (exhaust) for the second ring and about ·004 in. for both third rings.

All rings have been in continuous use since the initial building of the gasifiers, representing over 3,000 hours of operation for each ring at December, 1959.

**Turbine and Gearbox**

The Alsthom turbine has operated satisfactorily and given no trouble at all. No maintenance or inspection has been carried out, and it is not proposed to inspect this unit until 12 months operation has been completed.

The Renk double-reduction gearbox has performed satisfactorily since the vessel was handed over.

This is the first example of a conversion to free-piston gas turbine propulsion to be carried out as a private venture, and it has been reported that, so far, the venture can be said to have been satisfactory and the engine has produced its rated output with a slightly better performance than expected and has done this while operating on a residual fuel. It is also encouraging to be able to record that both the owners, Messrs. Wm. France, Fenwick & Co. Ltd. and Messrs. Smith's Dock Co. Ltd. state they are very satisfied with the performance achieved, and further it is understood that the engine room staff are enthusiastic about the installation and have confidence in the engines.

**Conclusion**

So far the free-piston sets that have gone to sea, or are at present building, are of relatively low power with comparatively few gasifiers. The future of this type of machinery would appear to depend largely on its reliability in service and whether experience shows that it offers any significant advantages for moderate powers over the orthodox diesel engine.

For higher powers it is interesting to note that Messrs. Fiat[6] have built an experimental unit developing 2,000 h.p. but no details of this machine appear to be available at the time of writing.


## ACKNOWLEDGMENTS

In preparing this paper the Author has been greatly helped by the work carried out in this particular field by his predecessors in the Engine Plans Dept., and by the data accumulated by them. In this connection he is particularly grateful to Mr. S. N. Clayton, now in Japan.

The Author would also like to express his thanks to Mr. S. Archer, M.Sc., and Mr. T. D. Shilston, for having had the opportunity of assisting in the work of plan approval of free-piston gas turbine machinery, but for which it would have been impossible to gain the necessary background and information.

The Author is also grateful to Mr. Maclennan, Editor, "The Marine Engineer and Naval Architect", and to the Motor Ship" for the use of printing blocks for the reproduction of some of the pictures and diagrams contained in the paper.

Thanks are also due to the following firms for permission to publish various diagrams and drawings: —

Messrs. J. & J. Denholm (Management) Ltd.

Messrs. Wm. France, Fenwick & Co. Ltd.

Messrs. The Bolton Steam Shipping Co. Ltd.

Messrs. Nederlandsche Maatschappij voor de Walvisvaart.

Messrs. Alan Muntz & Co. Ltd.

Messrs. Rankin & Blackmore Ltd.

Messrs. Smith's Dock Co. Ltd.

Messrs. Societe Alsthom.

Messrs. Power Jets (Research & Development) Ltd.

Messrs. Associated Electrical Industries Ltd.

Messrs. Stone Marine Engineering Co. Ltd.

It is also desired to express appreciation of the work of the Printing House Staff for the presentation and arrangement of the text and illustrations and to thank the Staff Association for the opportunity of presenting this paper.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Printed by Lloyd's Register of Shipping at Garrett House Manor Royal, Crawley, Sussex, England

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# Lloyd's Register Staff Assocation

Session 1960 - 61

Paper No. 1

Discussion

on

Mr. R. J. Hook's Paper

# SOME NOTES ON FREE PISTON GAS TURBINE MACHINERY FOR MARINE APPLICATIONS

LLOYD'S REGISTER OF SHIPPING

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Discussion on
Mr. R. J. Hook's Paper

# Some Notes on Free Piston Gas Turbine Machinery for Marine Applications

## Mr. S. Archer

Mr. Hook, with his usual careful attention to detail and clarity of description, has produced a most useful pocket size reference work on the free piston gas turbine for which his engineer colleagues, present and future, at home and abroad, will surely be much indebted.

I find little to criticise in the paper and much to praise. The many excellent sectional drawings, diagrams and photographs make the text unusually easy to follow. I thought the tabulation of Register Book particulars for all existing classed free piston-engined ships on page 5 a particularly happy idea and it is noted that space has been allowed for insertion of further ships and their data as and when required. The free piston "family tree" on page 3 is also both informative and convenient.

Among the advantages of the free piston engine is that although it deliberately makes use of vibration and resonance for its linear motion (the mass/elastic system comprising piston and air/gas cushions, respectively) it can crow over its conventional diesel brother in that such vibration is a servant rather than a potentially dangerous enemy capable of inflicting grievous bodily harm, due to critical speeds, in the shape of broken shafts, wear and tear of running gear, etc., etc. This is a factor which is perhaps not sufficiently emphasised when weighing up the various "pros and cons" of free piston machinery.

On the debit side, of course, the noise and pulsation aspect is admittedly of nuisance value and one's sympathies lie with the early ship's engineers who had to contend with it. However, now that the problem has been largely eliminated by various means as indicated by the Author, this can hardly be considered a major factor.

Could the Author give some particulars of the new "twinned" gasifier units (G.S.2.34) recently reported to have completed some 4,500 hours of testing on four prototype units? Is it correct that these units have shown some appreciable reduction in pulsation and noise level apart from reduced weight and space?

It is noteworthy that the U.S.S.R. has also shown keen interest in free piston developments (October, 1960) to the extent of seven 10,000 ton d.w. cargo ships with 4,000 s.h.p. direct-reversing turbines through triple reduction gears to a single screw, this latter a comparatively rare feature in merchant practice. So far as is known, Russia has no indigenous large slow-running high power direct reversible diesel engines and has so far concentrated on medium and high speed engines. Thus, it is understandable that the free piston engine would hold particular appeal in that country.

I understand that in East Germany a recent twin screw passenger vessel has been completed with combined geared diesel and free piston gas turbine machinery on each shaft. Could the Author give any further details of what appears to be a novel and most interesting machinery arrangement?

On the score of overall thermal efficiency, there is no doubt that the free piston gasifier/geared gas turbine combination is some 15 per cent less efficient than the direct-coupled turbo-charged 2-SCSA heavy oil engine.

| Thus: — | *Brake thermal efficiency %* | *lb./b.h.p. hr.* |
|---|---|---|
| Turbo-charged 2-Sc Diesel | 37–42 | 0·38–0·34 |
| Free piston/geared G.T. | 33–35 | 0·43–0·405 |

The gasifier itself, however, owing partly to its much higher (2–3 times) compression ratio and partly to improved combustion and lower cooling and mechanical losses, is somewhat more efficient than the direct diesel and in terms of gas horsepower can convert up to 43–45 per cent of the heat in the fuel, say 0·33–0·31 lb./g.h.p. hr. The irreversible heat transfer from high temperature flame to compressed air charge will in fact be less than in the direct diesel, since, first, the charging air is at a higher initial temperature at entry to cylinder, say 450° F., instead of say, 100° F. for an after-cooled turbo-blower, and, secondly, due to the much higher compression ratio, say 30 to 40 instead of 12 to 16, the final temperature of the charge at ignition may be over 1,000° F. higher, which also partly explains the free piston gasifier's facility for burning boiler oil.

Where then do the losses come in? Would the Author agree that these are roughly split between lower conversion efficiency, i.e., heat in gas to propeller shaft work (say, 0·85 gas turbine efficiency $\times$ 0·96 d.r. gen. efficiency$=$0·80) as compared with about 88 per cent mechanical efficiency in the turbo-charged direct diesel, and the aerodynamic losses between gasifier and turbine due to the relatively large mass flow, the latter, therefore, accounting for about one-third of the total 15 per cent difference?

Assuming that little can be done about the gearing efficiency and that having optimized turbine efficiency, preferably by omitting the reversing turbine, and having gone to either C.P. propeller or, in small powers, not more than, say, 1,000 s.h.p., to reverse-reduction gears, what then are

the future possibilities for recouping the remaining 7–8 per cent deficiency? It is possible that by still further increasing compression ratio and adopting compressor after-cooling, some of this leeway will be made up but not much can be done about the aerodynamic losses in valves and ducting. Furthermore, unless radical metallurgical and lubrication improvements are evolved for the gasifier combustion chamber and piston components, these advances in efficiency could perhaps be too dearly bought! I should value the Author's views on these points.

Leading from this, it has been reported that S.I.G.M.A. are developing a strengthened central combustion chamber belt, presumably having in mind the desirable higher compression ratios to give still better gasifier efficiencies. The new design is reported to include only three fuel valves, each of larger capacity than that of the six valves in the existing design and all of them of the direct injection type compared with the four direct and two pre-combustion valves in the present G.S. 34 gasifiers. Has the Author any further information on this?

Finally, the question of the best and most suitable type of ship for the free piston engine is a vexed one. Owing to its undoubtedly inferior part-load efficiency in consequence of the need for blow-off, or re-circulation, below about 25 per cent full power (say $\frac{5}{8}$ full speed), it would not be at its best in services demanding a great deal of manœuvring such as tugs, ferries, harbour or river craft. On the other hand, with the desirable substitution of the C.P. propeller for the astern turbine, the free piston engine would be well suited to such two-condition services as whale-catching, trawling (ability also to run at very low propeller thrusts is here an advantage over the direct diesel) or ocean towing, salvage vessels, etc. There would also be a field for medium to large coasting vessels, but personally I cannot see much future in the larger powers. Perhaps the Author will have other views, and, if so, it would be valuable to hear them.

### Mr. T. D. SHILSTON

The type of machinery to which this paper refers is new in the Association's records and Mr. Hook deserves our thanks for presenting us with such a full and descriptive contribution to our transactions. The great majority of surveyors will have had no direct contact with free piston gas turbine machinery and this informative paper will be greatly appreciated by them.

This machinery has something of both the diesel and the gas turbine in its make-up and seems to succeed in making the best of both worlds. The diesel component avoids crankshaft, crosshead and bearing troubles whilst the gas turbine does not have the metallurgical problems that the normal high temperature gas turbine has to contend with. Indeed the gas temperature under normal conditions is less than in a modern steam turbine.

No doubt this machinery will have its own troubles but from service records quoted in the paper they do not to date appear serious. In diesel engines we get scavenge trunk fires. Can the Author state if engine case fires are common and what is done about them?

The fuel consumption is higher than for comparative diesel machinery, but the weight and space occupied is appreciably less giving more cargo capacity.

Gas horse power is a new term to most of us and a definition would, I think, be helpful. For instance, does the formula on page 9 allow for expansion down to atmospheric pressure?

Some early trouble was experienced with the fabrication of the gas ducting. The material originally chosen, although suitable for the temperature, proved to be extremely difficult to weld and was eventually abandoned in favour of a more readily weldable material.

The design of the expansion pieces in the gas ducting is of interest. Made from a number of layers of stainless steel of almost paper thickness and deeply corrugated they are beyond normal heavy marine engineering practice. The attachment of the laminates to the end flanges by means of welding caused some head scratching in the Plans Department and one had to bear in mind that the working pressure in the line was only 50 lb./sq. in., much lower than normally met with in power piping.

The gas turbines themselves, as Mr. Hook remarks, owe more to aircraft practice than to marine steam turbines and in dealing with the plans one had to bend one's mind to new conceptions and forget old ideas as to what was fit and proper for a ship. As an example of this the size of bolts could be mentioned. As a result of knowing the things that can happen at sea the marine engineer tends to regard any bolt less than $\frac{5}{8}$ in. dia. as being rather flimsy. When dealing with plans of gas turbines, we were horrified, therefore, to be faced with countersunk-headed screws of 3/16 in. or even $\frac{1}{8}$ in. dia. On remonstrating gently with the designer on this score, we were assured that this was normal practice for this type of turbine. What a ham-fisted second engineer will make of them I tremble to think.

The Author rightly stresses the flexibility of arrangement for this type of machinery. The gas turbine itself is remarkably small for its output and the gasifiers can be placed in any suitable place so that the engine room can be made quite small. This, of course, is of great interest to the shipowner.

You will see from the paper that free piston gas turbine machinery is to be installed on a whale catcher. This indicates a high expectation of reliability since whale catcher machinery has to work under extremely rigorous conditions with a minimum of maintenance, once on station. This is a great tribute to inventors, designers and constructors.

MR. C. DEARDEN

I must extend my thanks to the Author of this paper for his clear exposition of the present position of the free piston gas turbine installation, his very factual survey shows clearly the progress made with this type of prime mover over the past decade.

It is clear that the attractive s.h.p. to weight ratio and the flexibility with which the component parts can be arranged add a new element to the art of accommodating machinery into the smallest space possible, reminiscent of Sir Harry Ricardo's proposals of 25 years ago. This no doubt will please the naval architects and those eager to take advantage of the new tonnage regulations. However, I do wonder what the engineers who may have to work in these increasingly cramped and noisy spaces may have to say about these latest technical innovations.

Whilst running my eye over the paper I was rather intrigued with the data given on page 4 for the G.S.34 unit, particularly in relation to the fuel consumption which, although good, is not yet comparable with the direct-acting diesel.

The losses noted between these two systems could be partly attributed to the mechanical gearing which would be at least 96 per cent efficient and the adiabatic processes in the turbine and working cylinders, these latter would be, say, 85 per cent efficient. Then, having regard to the high maximum pressure and M.I.P. recorded, I am mystified as to the source of the remaining losses.

My opinion at the moment (which is open to the Author's correction later) is that the air supply from the compressor cylinder is considerably in excess of the combustion cylinder volume. Thus the temperature in the gas cylinder at the opening of the exhaust ports is high, and is subsequently diminished by dilution with the excess air from the compressor cylinders. The temperature at the scavenge ports when uncovered by the piston could be expected from the data provided to be about 1450° F. and the temperature of the incoming air perhaps 240° F. so that the resulting mixture supplying the turbine is as given, viz. 850° F.

Now the axioms of Carnot lay down that the engine must take in heat at the highest possible temperature and reject it at the lowest possible temperature, but it should be noted that this refers to 1 lb. of the substance, whilst for the thermal system under notice there is an increase in the weight of the fluid at the inlet to the turbine and although the reject heat temperature is lowered this undoubtedly represents an irreversible thermodynamic loss, which I do not think can be avoided so long as the full swept volume of the compressor pistons is allowed to pass through the working cylinder and on to the turbine.

In the large two-stroke supercharged diesel engine the scavenge volume could be expected to be about 1·3 times the swept volume of the cylinder so that we may say that substantially 1 lb. of working fluid has passed from the highest to the lowest temperature at rejection. So it would appear that the free piston system with regard to fuel economy is inherently less efficient at the moment.

Further, although I am aware that the low admittance temperature to the turbine has many desirable features, it should not be forgotten that with increasing numbers of gasifier units employed when connected to one or more turbines, care would have to be exercised in proportioning the length of ducting since further thermodynamic losses could be expected. I would be glad to hear the Author's opinion on the above problem.

MR. S. N. CLAYTON

The Author has given us an excellent paper on Free Piston Gas Generators particularly in his coverage of recent applications and operational experience.

I recall that when plans of the G.S.34 and C.S.75 types were originally dealt with, questions were raised concerning the possibility of fires and explosions in the engine case and the necessity of fitting explosion relief valves. It would be of interest if the Author would state whether experience has shown such fittings to be necessary or not and the present attitude towards such fittings.

It is noted that the C.S.75 type has been referred to in a brief comment only and it is concluded that this type has had no marine application. Could the Author state the results of operational experience with this type on land and in particular whether the materials used have proved satisfactory, it being recalled that the original materials specified for this type were inferior to those used in the G.S.34 generator.

As stated in the paper, Messrs. Nippon Kokan K.K. are the only sub-licensee in Japan and part of their Tsurumi Works has been tooled up for the manufacture of G.S.34 gas generators. Although a number of enquiries have been received by the firm regarding possible conversions none of these has as yet resulted in an order being placed.

In an endeavour to promote the machinery in Japan, N.K.K. have therefore built a 2,000 h.p. tug boat for their own use and for demonstration purposes. The machinery consists of two G.S.34 type gas generators supplying two gas turbines driving reversible pitch propellers. The gas turbines have been built by Nippon Kokan under licence from Rateau. At the time of writing installation of the machinery is complete but sea trials have not as yet been completed.

A summary of the shop trial results for one of the gasifiers installed on this tug boat is shown in Fig. A, and the general arrangement of the tug and its machinery in Fig. B.

MR. E. L. GREEN

**Starting the Engine**

Could the Author enlarge a little on the actual provisions made for starting the engine and describe in more detail the operation whereby the pistons are moved to their outer dead points?

On page 1 it is stated that "fuel is injected as the pistons approach their inner dead point (I.D.P.) and combustion occurs". What a wealth of optimism there is in this sentence! Many of us who have had experience of the blast air injection engines will remember that although all requirements had apparently been fulfilled, combustion just didn't occur!

Of course, improvements have been made in the diesel engine since that time, but it would be interesting to know just how long it would take for free piston engine pistons to be moved to their outer dead points assuming that combustion did not take place the first time.

**History**

The Author gives us a very interesting account of the origin of the principle of the free piston engine, but the type of engine which forms the subject matter of this paper, namely the G.S.34, was entirely developed by Messrs. S.I.G.M.A. under the direction of Mr. Huber who, incidentally, was at one time assistant to Professor Stodola.

The "magnum opus" then, of Messrs. S.I.G.M.A. is the G.S.34, the prototype of which was constructed at the firm's works at Venisseux in France in 1946 and bears the Serial No. 1.

**Synchronising Mechanism**

As the Author states, there is a mechanical connection between the pistons which is illustrated in Fig. 5, page 8.

It may be of interest to consider the evolution of this particular mechanism and its progressive development as shown in Figs. C, D and E hereunder.

**Operation under working conditions**

Chantiers de l'Atlantique Penhoet-Loire started building free piston engines at their Saint-Denis works some three or four years ago for main propulsion units intended for small vessels for the French Navy.

The French Naval Authorities required that the firm constructed a replica of the actual engine room which was to be used in service (there were a number of identical vessels for this contract) and that each propulsion unit, which included two sets of G.S.34 free piston engines, was run continuously at full power for, if my memory serves me right, 100 hours.

As far as I know, the operating tests were entirely successful, but I must say that in a confined space the pulsation effect of the intake air has, in my opinion, an unpleasant physiological effect inducing a certain mental dullness—of a temporary nature let me hasten to add!

In conclusion I would like to thank the Author for a most interesting and informative paper.

### Mr. P. F. C. HORNE

It would be of interest if Mr. Hook could provide data on the comparative performance of the two conversions made by Wm. France Fenwick & Co., viz., g.t.v. *Goodwood* and m.v. *Birdwood*. I understand that these conversions were based on ships of similar tonnage. Perhaps data on fuel and lubricating oil consumption would give a basis for comparison.

### Mr. P. FEDOROFF

The gasifiers on the *Morar* are secured into the ship by four $1\frac{1}{4}$ in. holding down bolts. These bolts appear to be completely insulated from the deck plating by Mascolite and Tufnol sleeves, washers and chocks.

I assume these are for thermal insulation but would like the Author to comment on this point. Does this mean that the framework of these gasifiers is at rather a high temperature or is this insulation for other purposes?

I have noted that the Author has stated the many advantages to be gained by installing free piston gas turbine machinery for marine propulsion. However, not much has been said regarding the disadvantages associated with this type of machinery.

Perhaps the Author would like to comment on this and include in his answer to the discussion a list of disadvantages which have been experienced in the running of this machinery for the interest of surveyors.

Finally, I would like to ask the Author if Mobilguard Marine 593 is a special type of oil or just a plain diesel engine cylinder oil.

## AUTHOR'S REPLY

To Mr. Archer

I am very grateful to Mr. Archer for his appreciation and interest and for his valuable contribution to the discussion which adds considerably to whatever usefulness the paper may have.

When all is said and done, a paper or discussion of any kind is not for the glorification of the participants but for the benefit of all who receive it and for that reason, I am pleased that this paper has provoked a fair measure of comment because that, after all, is where progress is made and purpose achieved.

With regard to the development of the "twinned" G.S.2.34 units it is understood that this new machine has been obtained by grouping together two G.S.34 gasifiers side by side. The main characteristics are: all the parts are identical to similar parts of the normal G.S.34; moving parts operate 180° out of phase and remain so within $\pm 2°$, independent of load or load changes. By this means, the compressor piston of gasifier A delivers scavenge air at a time when the scavenge ports of gasifier B are opened, which has been stated to result in a net reduction of delivery losses due to storage of air in the engine case.

It is also understood that tests on intercooling between the air compressor and diesel cylinder have been carried out, and it would appear that

similar gains to those obtained with crankshaft diesel engines should be achieved. The fact that the inlet and exhaust pulsations are dephased by 180° has been stated to make possible a reduction of dampening intake and exhaust volumes, which assist in a decrease in pulsation and noise level. The twin cylinder design is claimed to reduce the space occupied by 40/50 per cent and weight by about 25 per cent.

The East German vessel to which Mr. Archer refers is the *Fritz Heckert,* a cruising liner. This ship has an unusual combination of machinery, so far as is known the only one of its kind in the world. It is a twin screw installation with a total output of 10,000 s.h.p. giving a speed of about 19 knots. Driving each screw there is an eight cylinder 2SCSA diesel engine having an output of 2,300 b.h.p. at 221 r.p.m. connected to the line shafting by means of an electro-magnetic coupling with a slip ratio of 221/117 r.p.m. at full power. Power is also supplied to each propeller by three G.S.34 gasifiers driving an Alsthom expansion reversing gas turbine which is connected to the primary shaft gear by means of a fluid coupling and thence to the line shafting by conventional double reduction gears. The gasifiers are of the SEP-Pescara type built by Messrs. Demag Modag and located in a separate space extending across the breadth of the ship aft of the gear case. A profile of the ship and machinery arrangement are shown in Figs. F and G.

On the question of losses and efficiency of free piston gas turbine plant versus that of turbo-charged direct-acting diesel machinery, I agree with Mr. Archer's analysis which rationally and concisely explains the main considerations concerning the differences to which he refers and which indicates some directions where improvements may be made. Increase of compression ratio would appear to be one of the less difficult means by which improvement could be effected and development work of this nature is believed to be in progress. Mr. Archer wisely gives a timely warning, however, that too radical a step in this direction could bring more trouble than it is worth. Nevertheless, as Mr. Archer mentions, it is understood that development work has resulted in an improved design of the central engine cylinder section forming the combustion chamber, and this is claimed to effect a decrease in stress at this critical part of some 25 per cent, in addition to a simplification of the fuel injection system. Studies on combustion have resulted in better flame distribution and lower exhaust temperatures. With regard to the type of ship suitable for free piston gas turbine applications Mr. Archer has given an accurate picture of the field in which this machinery is found, as may be seen from the accompanying table (Fig. H). This reflects the trend to some extent and shows that, so far, seven different categories of vessels have been fitted with free piston machinery. This ultimately will yield interesting results when sufficient experience has been accumulated to indicate the suitability of this type of machinery for different types of service. Similar diversity is found in the turbines, reversing arrangements and reduction gearing. Time will enable comparisons to be made of their respective merits. It would certainly appear that at the present stage of development there is little future for free piston machinery in the larger powers.

To Mr. Shilston

I would like to thank Mr. Shilston for his kind remarks and take this opportunity of expressing my appreciation of his guidance and experience during the period I have been connected with plan approval of the type of machinery which forms the subject of this paper.

Mr. Shilston has rightly drawn attention to the omission of a definition of the term Gas Horse Power and this is now given below.

**Gas Horse Power**

This expression is used to define the thermodynamic work done by the gas on the diesel engine piston during adiabatic expansion from the combustion pressure down to atmospheric pressure and is therefore a measure of the power developed in the diesel cylinder of the gas generator. During an adiabatic expansion, of course, all work done is performed at the expense of the internal heat energy of the gas. The accompanying heat drop in the gas takes place from the initial combustion temperature to the outlet temperature from the gasifier at the instant at which the exhaust ports commence to open, and is measured in heat units per unit weight of gas. The gas horse power is therefore the product of the adiabatic heat drop and the mass flow of gas per unit time.

The meanings of the symbols used in the expression on page 9 are as follows:—

m = Mass flow
T = Gas Delivery Temperature, Absolute
$P_1$ = Gas Delivery Pressure, Absolute
$P_2$ = Atmospheric Pressure, Absolute

$$\gamma = \text{Ratio of specific heats} = \frac{C_p}{C_v}$$

$$= \frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}$$

The question of engine case fires raises some interesting points and highlights some of the difficulties overcome in the development of the gas generator up to the present time.

With prototype G.S.34 gasifiers it is understood engine case fires tended to occur when the internal surfaces became coated with oily carbonaceous deposits which in the presence of scavenging air temperatures of the order of 220° C.–240° C. (428° F.–464° F.) tended to ignite.

It has been stated by Messrs. R. M. Hosie and G. M. Barrett, M.B.E., T.D., B.Sc., in a recent paper to the Lubrication Group of the Institution of Mechanical Engineers entitled "Considerations of the Lubrication of Free-Piston Gas Generators" that the cause of excessive deposition is usually an indication of an increase of one or more of the factors responsible for deposition at normal rates.

These are poor combustion, blow past, overloading and use of an unsuitable lubricant.

The accumulation of excess oil on the internal surfaces forms gummy lacquers and ultimately hard coke-like deposits. In time such formation on the air compressor delivery valves prevents them closing properly. Subsequently these valves become very hot due to the wire drawing of the air delivered through them and eventually the output of the compressors may become so restricted, due to the build up of the deposits, as to stop the gasifier due to lack of air to support combustion. Further, the mixture of hot air and fine oil droplets may burn and result in stoppage of the gas generator from lack of oxygen. The solution to these troubles was found in the prevention of over-lubrication, elimination of hot points and the use of more suitable lubricants. It is worth noting that the general construction of the G.S.34 type gasifier is such that the lubricating oil delivery connections to the diesel cylinder from the externally mounted lubricator pass through the engine case scavenge belts and as these delivery lines may be of some length, the cylinder lubricating oil may lie in these lines for an appreciable period under high temperature conditions. Obviously it is, therefore, important that the cylinder oil used should have adequate thermal stability to withstand high temperatures and that no breakdown products be formed within the delivery pipes to affect the free flow of the lubricant. The present position, therefore, seems to be that the matter of lubrication is one that is engaging a good deal of attention and that further developments can be expected as experience with free piston gas generators progresses.

It may be anticipated that such development will proceed along three main lines:—

1. Redesign of engine components.
2. Improvement in lubrication methods.
3. Development of more suitable lubricating oils.

It is clear that if the free piston engine is to maintain or increase its application in the marine field or elsewhere, development must be towards greater power, economy, efficiency and reliability. These will inevitably result in an increase in the severity of the conditions to be met and sustained by the lubricating oil and the matter will therefore continue to be one of great importance.

As a further antidote to scavenge case fires water cooling of the compressor head plates carrying the compressed air delivery valves is employed, and this has helped to reduce the discharge air temperature and so decreased the tendency for deposits to form on the valves.

The deposit forming properties of the piston cooling oil is also important since any leakage of this oil around the various glands finds its way into the scavenge air case. This necessitates the use of a piston cooling oil having suitable properties to resist the tendency to form deposits.

In view of the measures developed to date it is thought that engine case fires are not now a serious problem with the free piston engine. As a safety measure should an engine case fire occur, and to prevent or minimise the effects of an explosion, it is the practice on free piston gas generators built under the Society's survey to fit an engine case relief valve.

### To Mr. Dearden

Mr. Dearden's references to the accommodation of machinery in the smallest possible space reminds me of a comment I heard a few years ago in connection with operational experiences at higher steam temperatures and the opportunities offered by changes in tonnage regulations permitting smaller engine rooms. It was said that it would be desirable for these changes to be accompanied by biological evolution in order to produce a breed of pygmy marine engineers having asbestos fur instead of skin!

If Mr. Dearden's fears about the effect of a noisy environment are realised, it might be suggested that the midget engineer should also be equipped with ear plugs. These comments serve the purpose of drawing attention to the topical question regarding noise levels in the engine rooms of free piston ships. Reports on this indicate that it is not objectionable provided suitable measures are taken to damp out the pulsation effect at the air intakes. This has been accomplished by two methods: (1) A free-running fan located in the air inlet ducting; (2) Arrangement of the air intakes away from the operational areas of the engine room. Both methods have been shown to be effective.

With his usual perspicacity Mr. Dearden has drawn attention to some of the most important points requiring investigation and solution before significant improvement can occur in the performance of the compound machinery represented by the free piston engine coupled to an exhaust gas turbine. It is clear that if this machinery is to make progress, development work will be necessary and there appears to be a number of directions in which this might take place.

1. Reduction of gas transmission losses through the ducting from the gas generator to the turbine.
2. Improvement of the thermal efficiency of the free piston engine.
3. Up-rating the gas generator by further supercharging.
4. Improving turbine efficiency.
5. The use of after-burning by means of which the gas temperature to the turbine could be increased.
6. The employment of a waste heat boiler system.

With regard to the quest for improved performance of this machinery, the following points are relevant. It can be shown that modern internal combustion engines operate very nearly on the constant volume cycle, very little fuel injection taking place at constant pressure. Accordingly, it is common practice for comparative purposes to evaluate the thermal efficiency on the basis of the

constant volume cycle. The standard efficiency for this being known as the Air Standard Efficiency which can be expressed: —

$$A.S.E.=1-\frac{1}{r^{(\gamma-1)}}$$

where r = Compression ratio
$\gamma$ = Adiabatic index

From this it can be clearly seen that as the value of the compression ratio increases so the efficiency increases. Here, then, is a possible field of investigation towards the improvement in the thermal efficiency of the gas generator and it is useful to digress slightly in order to present a fuller picture of this aspect, so far as it affects the free piston engine at present and could influence it in the future. In a direct-acting diesel engine mechanical and structural considerations limit the compression ratio to about 22:1. In a "straight" gas turbine metallurgical considerations imposed by maximum temperatures in the combustion chamber and turbine limit the compression ratio to about 7:1. In the free piston engine the gasifier compression ratio is not limited by these reasons and having no crankshaft allows very high compression ratios to be used. At present these are between 40 and 60:1 and it has been stated that 80:1 is within the range of moderately short-term development work. Experience will show whether this limit can be exceeded. Clearly these are steps along the Carnot path. As Mr. Dearden says, one of Carnot's important principles is that an engine must take in heat at the highest possible temperature and as the compression pressure is increased due to increase in compression ratio, so also is the temperature at which heat in the fuel is added. Again, as Mr. Dearden reminds us, Carnot tells us that an engine must reject heat at the lowest possible temperature. In the compound diesel-cum-turbine engine which this machinery represents where the turbine component is capable of accommodating large volumes of gas at low pressure and where the high pressure part of the cycle is performed with high efficiency (by reason of the high compression ratio) in the gas generator, the overall expansion ratio can be shown to be the product of the expansion ratios in each component.

The combined effect of this enables Carnot's second principle to be approached. However, the thermal efficiency of the gas generator itself which has been stated to be in the region of 43 per cent is offset by losses in gas transmission and reduction gearing and thus the overall thermal efficiency of the free piston engine is at present below that of the direct-acting diesel engine. Nevertheless, reduction in the internal losses in the gas generator and improvements in turbine efficiency should narrow the gap.

It is perhaps not irrelevant to comment that direct acting diesel engines appear to be working at the upper limits of their efficiency and have been so doing for a period of some 25 years or more, this including constant research and development effort. The noteworthy absence of crankshafts, connecting rods, bearings, camshafts, chain drives and flywheels in the free piston engine must surely make for a simpler and cheaper machine and easier or less maintenance.

As Mr. Dearden says, the air supply from the compressor is in excess of that required for combustion of the fuel in the diesel cylinder and at the present rating is in the region of 2:1 at full power. The effect of this must be to reduce the temperature of the gas slightly (this being further attenuated by the scavenge air), the overall effect being contrary to Carnot and causing the result to which Mr. Dearden refers. In the present arrangement it is difficult to see how this heat loss can be avoided. Conceivably, since a certain design mass flow is required, it would appear that a special arrangement of after-burning might be the answer since this would allow air not required for combustion of the fuel in the diesel cylinder to be bled from the compressor at a suitable pressure and heated in a combustion chamber to the required temperature. An after-burner consists of a vessel connected in the main gas duct to the gas turbine through which gas from the gasifiers is passed. It is fitted with suitable oil burners, ignition and controls and is suitably insulated.

It should be added that although after-burning does not increase overall thermal efficiency (in fact it can be shown that a decrease of a few per cent would occur), it does permit nearly 30 per cent additional power to be obtained from the turbine with an inlet temperature of 1,200° F. (650° C.). This can be accomplished in a chamber of moderate physical dimensions owing to the high heat release per unit volume, with convenience of location. Other useful characteristics are: (1) Simplicity of construction; (2) Instantaneous response to control; (3) Variability of gas temperature from the after-burner.

As a further alternative for improved performance the possibility of a combined gas/steam cycle could be considered, since the gas delivered from the gas turbine comprises about 80 per cent of unburnt air at a temperature of say 500° F., so that this air could be used to sustain combustion under a steam boiler to generate steam driving a geared steam turbine coupled to the shaft also driven by the geared gas turbine.

However, neither of these last two variants has been tried yet.

A further requirement which this machinery must undoubtedly satisfy in order to achieve wider use is obviously its ability to use high viscosity fuels with equal facility to that demonstrated by the crankshaft diesel engine. It has been shown to some extent that the gas generator can run on such fuel but the question of deposits and corrosion in the turbine is of vital importance, especially in the inlet nozzles, since restriction to gas flow here will markedly affect performance.

It is fair to say that even at its present stage of development the free piston engine compares reasonably well with the conventional diesel engine and further improvement can be expected

in power/weight ratios and specific fuel consumption as a result of increased compression ratios.

To Mr. Clayton

I am obliged to Mr. Clayton for his interesting contribution describing developments in Japan. So far as is known to the Author the tug boat application referred to is the first of its type and its eventual outcome is awaited with interest. It certainly seems to demonstrate that free piston gas turbine machinery possesses the necessary features of flexibility, manœuvrability and reliability essential for tug boat service having as its inherent characteristic, operation in confined waters, where the qualities referred to above are absolutely imperative for obvious reasons.

With regard to engine case explosion relief valves the Society's present requirements are that these should be fitted. The 50 mm. bore valve is designed to ensure reliable action in the event of its operation becoming necessary. The valve body is of cast steel with stainless steel seat and valve.

So far as is known to the Author there has not yet been an engine case explosion. However, the provision of one relief valve on the engine case of each unit is regarded as a prudent and desirable safety precaution. In this connection it might be opportune to add that consideration should be given to the shielding of possible discharge from an engine case relief valve, depending on its relative position to nearby gratings and platforms accessible to personnel and to its proximity to adjacent vulnerable fittings.

The marine application of the C.S.75 type free piston gas generator to date is limited to two 200 kW auxiliary electrical generating sets and so far as is known neither of them have done any extensive running, so perhaps it is a little early to comment on operational results.

It is believed the materials used in the construction of the C.S.75 gasifier have proved satisfactory.

No information appears to be available regarding land applications of the C.S.75 in the United Kingdom.

To Mr. Green

With regard to a fuller description of the starting procedure the following may be of assistance.

The whole process of starting, running and stopping a gasifier is carried out by the movement of the control handwheel which has marked upon it six positions numbered 0 to 5 inclusive. Each position provides the control for a certain operation in the complete sequence so that to start the gasifier, the control handwheel is placed in the appropriate position to admit air from the starting air receiver to a small cylinder called the manœuvring cylinder, the function of which is to move the pistons to their outer dead point. Whilst this is happening, air trapped in the cushion cylinder is allowed to escape by a pneumatically controlled relief valve, thus ensuring that the pistons remain at the O.D.P. Moving the handwheel to the next position opens the air start valve and admits air through the balance pipes simultaneously to both cushion cylinders thus forcing the pistons rapidly together. As the pistons approach the inner dead point the synchronising link gear operates the fuel pump and injection and combustion occurs. Further movement of the handwheel closes the air starting valve and the control is then in the running position. Movement to the next position causes the fuel pump plunger to be held up by compressed air, no fuel is delivered and the engine stops.

It is not known to the Author exactly how long it takes to move the pistons to the O.D.P. but it would appear from the ease of control facilitated by the movement of the handwheel that such a move could be carried out very quickly and that the time factor probably compares very favourably with that required in the case of the direct acting diesel engine in the event of a false start and can be measured in terms of a very few seconds.

I am interested to hear Mr. Green's remarks on his experience with blast fuel injection. However, experience is the best teacher of all and I feel sure that the fuel injection equipment on the G.S.34 has profited thereby and may be regarded with perhaps a little more confidence than the old blast gear, although in all fairness it must be stated that blast injection gave trojan service for many years and "solid" injection was regarded with not a little scepticism at its inception. It is interesting to conjecture whether the suspicion and distrust which heralded the advent of the marine diesel engine is in some measure somewhat akin to the regard in which the free piston engine is held to-day. No one would deny the enormous progress which the direct acting diesel has made over more than a quarter of a century, particularly in the last decade and even more so in the last two or three years in what has become known as "the large bore sweepstakes" where we now have powers of the order of 2,000 to 3,000 b.h.p. per cylinder. What does the future hold? It is reasonable to suggest that free piston gas turbine machiery will benefit by the progress and experience in both the diesel and the gas and steam turbine fields, in the development by our metallurgical friends of still better materials for high temperature service, to mention only one aspect, albeit an important one, which may eventually materialise if the economic spur is sufficiently sharp. It is quite certain that if free piston gas turbine machinery is going to develop at all in the marine field it must be shown capable of progress towards higher powers and to have worthwhile advantages in the face of competition from the established forms of propulsion. In this connection it has been stated that the G.S.34 has run experimentally for short periods at some 35 per cent above its current continuous maximum rating and the possibility of supercharging to double the output has been examined. This seems to indicate that free piston gas generators capable of producing 2,000 s.h.p. output per unit may be the next step in the evolution of this machinery. However, experience with the present design will undoubtedly determine the

detailed direction which development will take and this will require a few years yet.

Again, using the direct acting marine diesel engine as a yardstick, it seems that progress is made, roughly speaking, in terms of a decade or so, since it is not too far out to suggest that the "forties" were the years of the 650 mm. bore engine, the "fifties" saw the 750 mm. bore and the "sixties" are seeing the 850 mm. bore engine. On this basis it might be that we shall not see a more powerful free piston gas generator fully developed and available for service until somewhere towards the end of the present decade. This is only rubbing the crystal ball, of course, but at least it makes interesting guessing.

TO MR. HORNE

The data requested by Mr. Horne is stated below, together with the leading particulars of both vessels.

| | *m.v. Birdwood* | *g.t.v. Goodwood* |
|---|---|---|
| Length overall ... | 328 ft. 6 ins. | 314 ft. 11 ins. |
| Extreme breadth ... | 44 ft. 6 ins. | 45 ft. |
| Draught Summer ... | 19 ft. $10\frac{1}{2}$ ins. | 18 ft. $7\frac{3}{4}$ ins. |
| Deadweight ... ... | 4,360 tons | 3,485 tons |
| Fuel consumption lbs/SHP hour ... ... | 0·38 | 0·43 |
| Total quantity of lubricating oil used on main propelling machinery per day ... | 22·5 galls. | 28·7 galls. |

Before conversion the M.V. *Birdwood* was propelled by a triple expansion engine developing 1,200 IHP at 60/65 rpm. Steam at 220 psi was supplied by two coal fired multitubular boilers and this plant gave the ship a speed of nearly ten knots.

The steam driven machinery was replaced by a Ruston 4SCSA turbo-charged nine cylinder 9 VOXM type diesel engine having a continuous power rating of 2040 BHP at the gearbox coupling when running at 435 rpm. Speed reduction is obtained through a 4 : 1 Hindmarch Modern Wheel Drive oil operated reverse reduction gearbox.

TO MR. FEDOROFF

In reply to Mr. Fedoroff I am of the opinion that the compressed fibre material sleeves, chocks and washers to which he refers are intended to act as a resilient mounting to absorb vibration and noise rather than for thermal insulation purposes, since it is not expected that the mounting of a free piston gas generator will be at a temperature very different from that usually experienced at the bedplate of a crankshaft diesel engine.

With regard to disadvantages associated with free piston gas turbine machinery there appears to be scant information available up to the present time and certainly nothing which could be described as a "list".

Possibly owners of this type of machinery could shed some light on this particular point, and indeed such enlightenment would be most welcome. However, it is reasonable to assume that this machinery will have its teething troubles as did the diesel engine in its early days, and it is also reasonable to conjecture that in the present state of the art such difficulties will be more rapidly overcome than has been the case with the diesel engine. From the point of view of Surveyors who may be called upon to survey free piston gas turbine machinery it is suggested that where applicable such examination as is usually carried out on a crankshaft diesel engine would be a satisfactory starting point, although clearly there will be special parts such as compressor valves and delivery plates, link mechanisms, balance pipe glands, etc., etc., which are largely peculiar to free piston machinery and may be subject to their own vagaries and defects. In addition, attention should be paid to the gas turbine rotor and stator blading, nozzles and manœuvring valves to ensure that these are in a satisfactory condition and free from deposits, since it has been found in practice that with some fuels such depositions have occurred with accompanying adverse results.

It might also be mentioned that, having regard to the pulsation effect at the air intakes, attention should be paid to the securing of the dampers and other component parts since experience has shown that vibration can loosen these. Difficulty has also been experienced on occasions with air locks in the fuel system and suitable precautions should be taken to ensure that these cannot occur. Care with regard to oil tightness in the hydraulic control system is also necessary, since leakage can cause defective operation of the components so controlled.

With regard to Mobilguard 593, this is a lubricating oil specially developed for use with free piston gas generators for reasons referred to in my reply to Mr. Shilston. It is understood similar oils have been developed by the major oil companies.

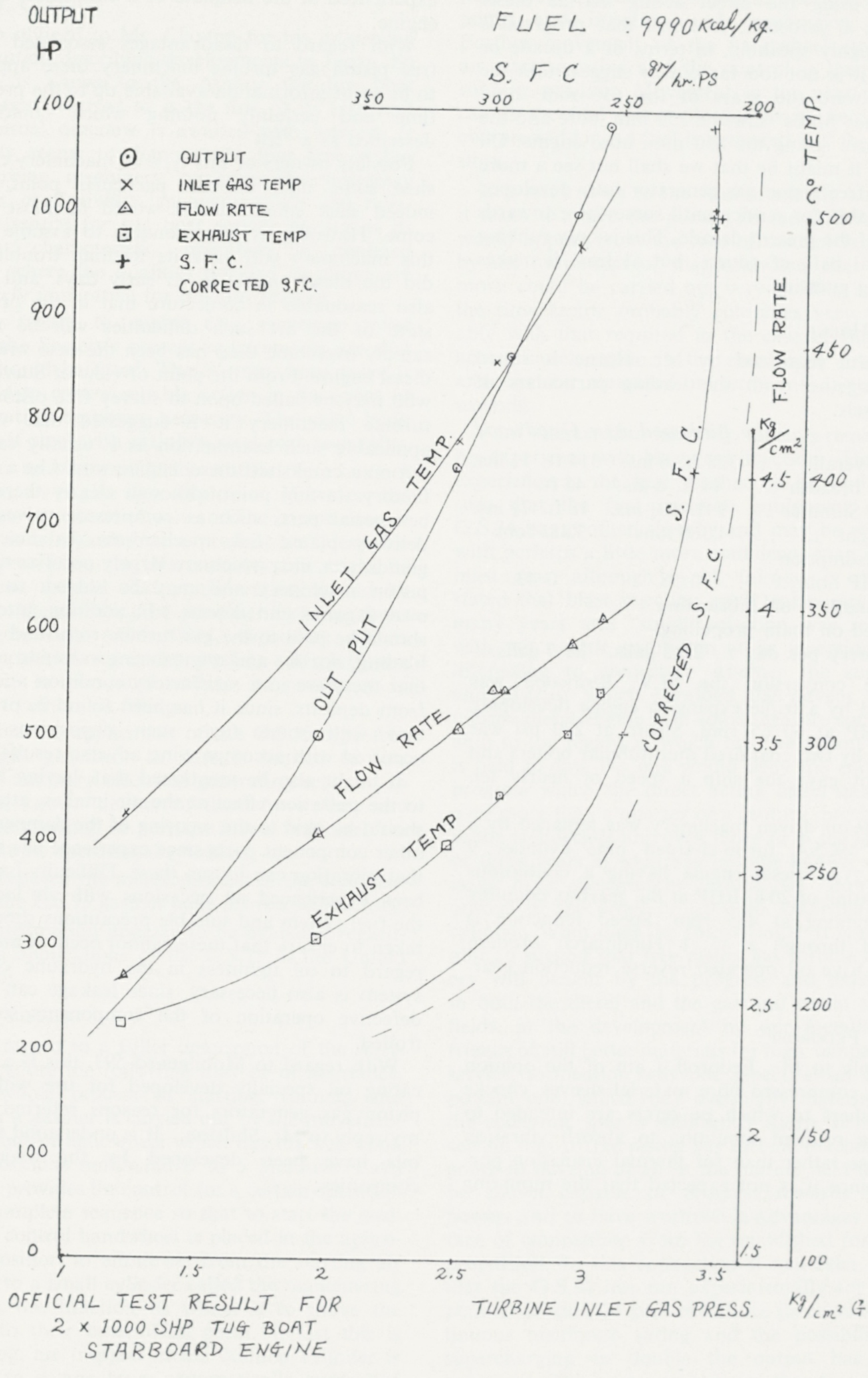
OUTPUT
HP
FUEL : 9990 Kcal/kg.
S. F C gr/hr.PS
350 300 250 200
°C TEMP.
1100 1000 900 800 700 600 500 400 300 200 100 0
OUTPUT
INLET GAS TEMP
FLOW RATE
EXHAUST TEMP
S. F. C.
CORRECTED S.F.C.
INLET GAS TEMP.
OUT PUT
FLOW RATE
EXHAUST TEMP
S. F. C.
CORRECTED S. F. C.
FLOW RATE
Kg/cm²
500 450 400 350 300 250 200 150 100
4.5 4 3.5 3 2.5 2 1.5
1 1.5 2 2.5 3 3.5
OFFICIAL TEST RESULT FOR
2 × 1000 SHP TUG BOAT
STARBOARD ENGINE
TURBINE INLET GAS PRESS. Kg/cm² G

FIG. A

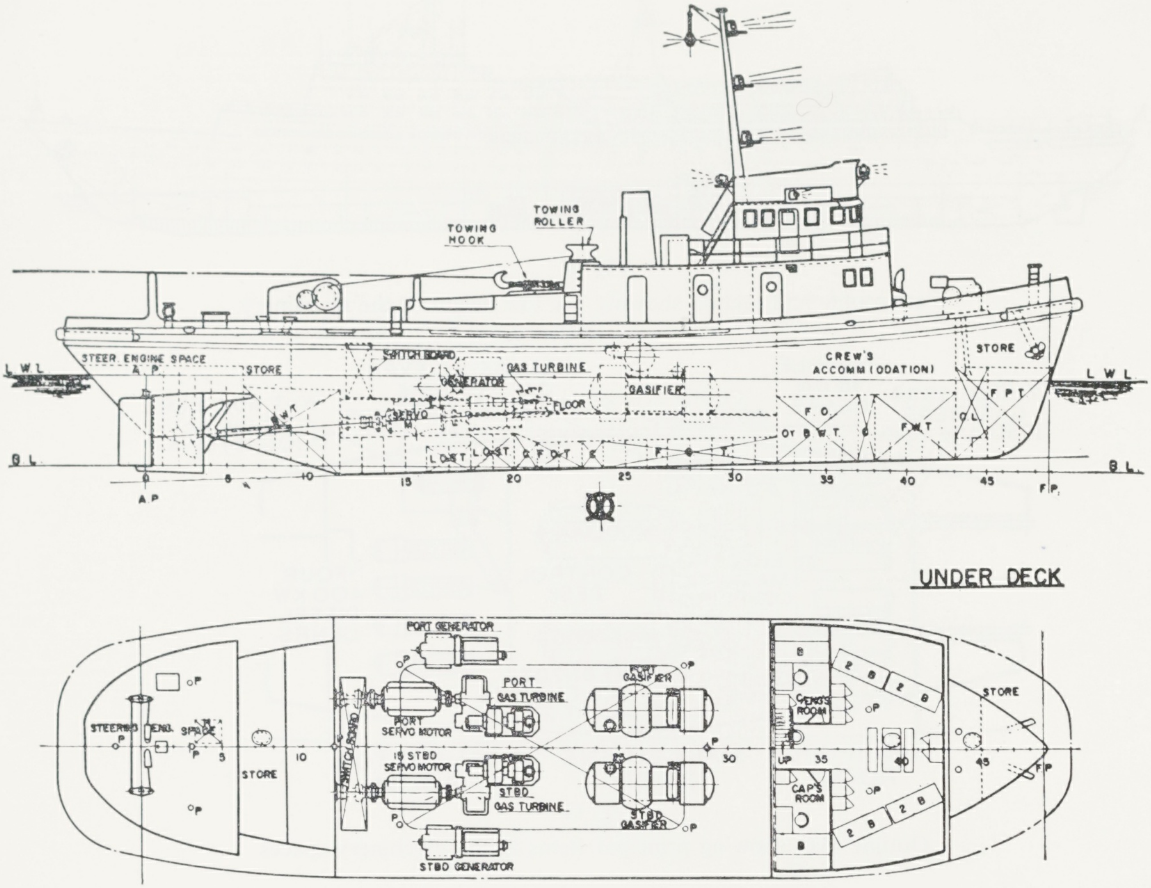


Fig. B

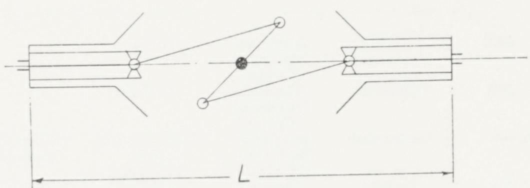

Fig. C

Oscillating Lever

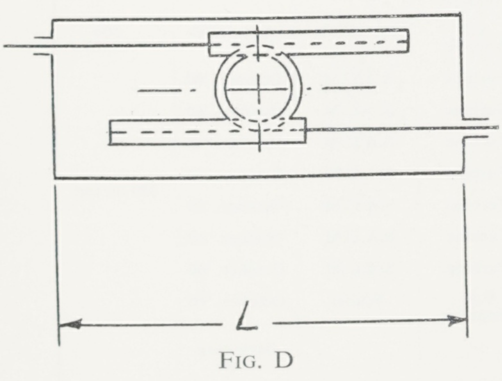

Fig. D

Rack and Pinion

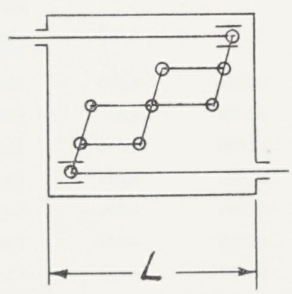

Fig. E

The arrangement shown in Fig. E of the well-known parallelogram mechanism is much shorter and is the one finally adopted

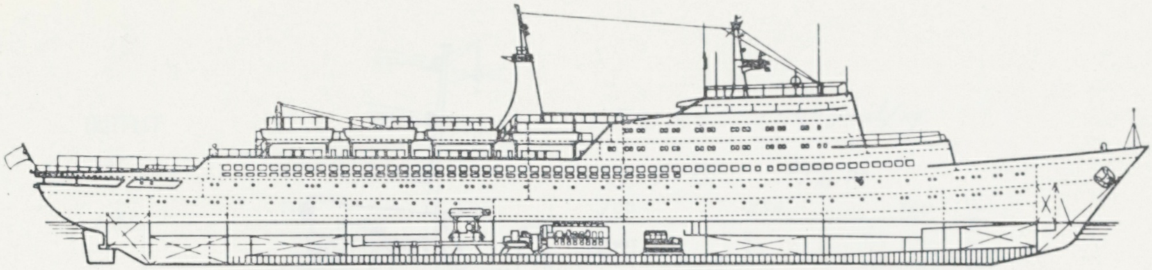

Fig. F

Part profile and section showing the low height of the machinery

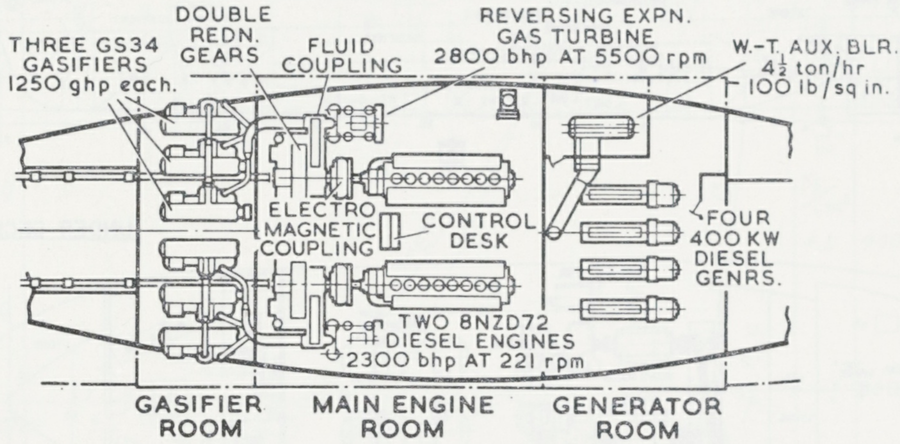


Fig. G

Outline plan showing principal items in the machinery spaces

**Table 1 Free piston-engined Merchant Ships**

| Name of Vessel | Tonnage D.W. | H.P. | Service | Builder | Reversg. Arrgt. | Reduction Gear | Date Commissd. | Number of hours of service |
|---|---|---|---|---|---|---|---|---|
| Cantenac ... | 1,200 | 1,200 | Coaster | Augustin-Normand-France | Turbine | — | July, 1954 | 22,000 |
| Corvo ... ... | 1,200 | 1,200 | Coaster | Augustin-Normand-France | Turbine | — | Feb., 1955 | 20,000 |
| W. Patterson | 10,000 | 6,000 | Cargo ship | Bethlehem Steel General Motors | Turbine and V.P. Propeller | Milled and ground | 1957 | 7,000 |
| Sagitta ... ... | 900 | 2,000 | Trawler | Demag-Rickmers | V.P. Propeller | Milled | Dec., 1957 | 18,000 |
| Morar ... ... | 7,000 | 3,000 | Ore Carrier | Lithgows Ltd. | Turbine | Fairfield S. B. and E. Co. | Oct., 1958 | 8,500 |
| Goodwood ... | 3,200 | 2,000 | Cargo | Smith's Dock | Turbine | S.A.C.M. | June, 1959 | 6,000 |
| Rembrandt ... | 13,000 | 4,000 | Cargo | Smith's Dock | V.P. Propeller | B.T.H. | Aug., 1960 | 200 |
| Geestland ... | 2,200 | 4,000 | Banana Carrier | Werkspoor C.A.Z. | V.P. Propeller | Stoeckicht | June, 1960 | 2,000 |
| Geestar ... | 2,200 | 4,000 | Banana Carrier | Werkspoor N.V.S. | V.P. Propeller | Stoeckicht | Aug., 1960 | 500 |
| Russian Vessels ... | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | 350 on test |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| | 10,000 | 4,000 | Cargo | U.S.S.R. | Turbine | S.A.C.M. | October, '60 | |
| Robert W. Vinke ... | — | 3,000 | Whaler | A.D.M. | V.P. Propeller | Wülfel | October, '60 | |
| Trig ... ... | — | 2,000 | Tug | Japan | — | — | Beginning 1961 | |

Fig. H

Printed by Lloyd's Register of Shipping
at Garrett House
Manor Royal, Crawley, Sussex, England

For Private Circulation amongst the Staff only

Lloyd's Register
Staff Association

Session 1960 - 61
Paper No. 2

# SOME NOTES ON VIBRATION PROBLEMS

by

A. R. HINSON

LLOYD'S REGISTER OF SHIPPING
71, Fenchurch Street, LONDON, E.C.3

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# Some Notes on Vibration Problems

**By A. R. Hinson**

## INTRODUCTION

In a vibrating system only four different types of force can act: spring, damping, inertia and exciting. There are therefore only four fundamentally different approaches to vibration problems: —

(i) Spring forces may be modified, e.g., increasing the diameter of the intermediate shaft in order to increase its stiffness.

(ii) Damping forces may be increased, e.g., arranging for a vibrating member to shear a viscous fluid.

(iii) Inertia forces may be modified, e.g., changing the size of a flywheel.

(iv) Exciting forces may be reduced, e.g., cropping the blades of a propeller in order to prevent the tips working in a region of high wake variation.

The purpose of these notes, which have been largely based on work done by the writer in the Society's Engineering Investigation Department, is to illustrate how one or more of these forces can be modified in order to eliminate or reduce unwanted vibration. An illusion of variety is given by the different ways in which the forces manifest themselves, but it is only an illusion, and the following examples, although concerned with such diverse items as safety valves, samson posts, gases, gearcases, hulls, boiler fronts, bridges and propeller shafts, tacitly repeat over and over again the theme of the four forces: —

$$\begin{matrix}\text{Spring} \\ \text{force}\end{matrix} + \begin{matrix}\text{damping} \\ \text{force}\end{matrix} + \begin{matrix}\text{inertia} \\ \text{force}\end{matrix} + \begin{matrix}\text{exciting} \\ \text{force}\end{matrix} = 0$$

### Gas Vibration

EXAMPLE 1

Vibration of a safety valve fitted on a length of ducting attached to a pressure vessel. (Fig. 1.)

When the safety valve lifted under excess pressure on test it blew steadily for a short period and then began to vibrate. The amplitude of vibration was shown by the lift indicator and it increased until the valve lid was hammering violently on its seat. The vibration extended to the waste pipe and ducting and the valve was closed manually to prevent damage.

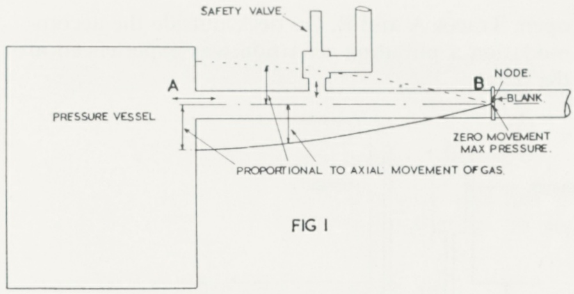



FIG I

Vibration of a safety valve fitted on a length of ducting attached to a pressure vessel

A pressure transducer fitted at the inlet to the valve recorded pressure fluctuations of frequency 14 cycles/sec.; maximum pressure amplitude $\pm 15$ lb./sq. in. The frequency of the valve spindle, measured at the lift indicator, was also 14 cycles/sec.

Calculations indicated that the natural frequency of the column of air in the length of ducting AB was also 14 cycles/sec.

An experimental check was made by opening the valve by hand and shutting it smartly; this caused a transient vibration having a frequency of 14 cycles/sec. to be picked up by the transducer. Calculations also indicated that the natural frequency of the mass of the valve against its spring was 14 cycles/sec.

Since it was impractical to alter the length of the ducting sufficiently, or alter the spring: mass ratio of the valve mechanism, attention was turned to the valve disc-holder. This was designed so that the kinetic energy in the escaping gas helped to keep the valve open. It was machined to increase the servo-effect of the escaping gas; the area upon which the gas acted was increased and the angle through which the gases were turned was also increased.

The valve did not vibrate on subsequent tests.

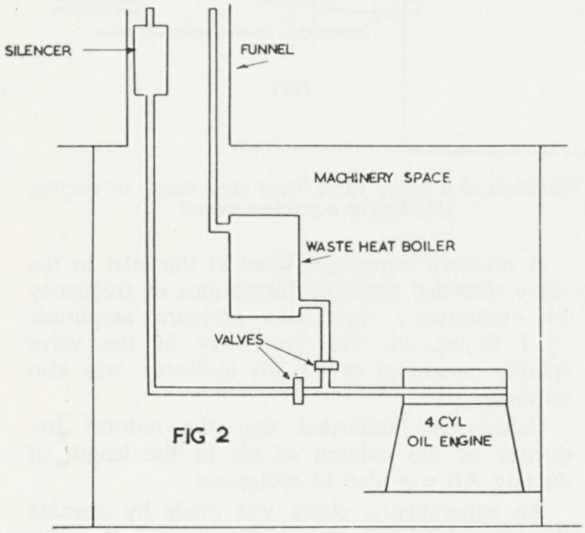
It appears that the turbulent flow of the gas through the safety valve vibrated the gas in the ducting and that the pressure fluctuations acting on the underside of the valve excited its mechanism. Variation in the valve lift occurred at the same frequency as the pressure fluctuations in the ducting, and accentuated them. The modification to the valve disc-holder increased the lift owing to the velocity of the escaping gas, so that when the valve tended to close during vibration and hence reduced the flow the spring was able to shut the valve and keep it shut.

EXAMPLE 2

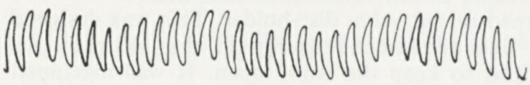
Vibration in the exhaust of a four-cylinder, two-stroke cycle, single acting oil engine fitted in a cargo ship. (Fig. 2.)

At a certain speed wooden bulkheads throughout the accommodation vibrated violently and noisily. The amplitude of the vibration could be changed by opening and closing portholes and doors, and increased greatly when the engine room door leading into the accommodation was

open, Traces A and B. On deck outside the accommodation a pulsating sensation was experienced in the ears.

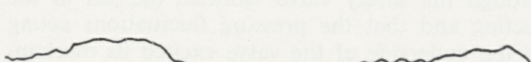



The column of gas in the exhaust pipe was excited to resonance by the pressure surges created when the exhaust ports opened. The movement of gas at the top of the funnel excited air in funnel and engine room and whenever the engine room door was open pressure waves entered the accommodation and shook sympathetic bulkheads



Trace A

Taken from wooden cabin bulkhead excited by exhaust gas vibration. Engine room door and cabin door open; pressure fluctuations admitted to one side of bulkhead only



Trace B

Same bulkhead when adjacent cabin door was open to equalise pressure fluctuations on both sides

Approximate calculations revealed that for engine firing frequency at the speed in question, the length of exhaust pipe was probably critical; it appeared that the column of gas in the pipe was excited to resonance by the pressure surges created when the exhaust ports opened. The movement of gas at the top of the funnel excited the air in the funnel and engine room and whenever the engine room door into the accommodation was open pressure waves entered the alleyways and vibrated sympathetic bulkheads.

When the exhaust gases were directed through the waste heat boiler the vibration was reduced.

A modified silencer (Fig. 3) was fitted which divided the exhaust into two paths, one longer than the other by half the length of a pressure wave. When the paths were reunited the pressure fluctuations cancelled out, and it is understood that the vibrations were eliminated.

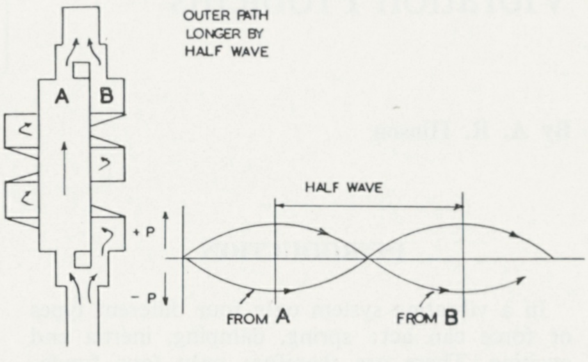



FIG 3

When the paths were reunited the pressure fluctuations cancelled out

The gas movement in the ducting and exhaust pipe in the above examples approximates to what is usually termed "organ pipe vibration".

In Fig. 1, if the gas at A is disturbed, a pressure wave travels to B and is reflected back to A. When the disturbance is cyclic and its period is the same as the time taken for the pressure wave to travel down the pipe and back again, resonant vibration occurs in the gas.

When vibrations occur sufficiently slowly in air they may be detected by the ear as distinct pulses, but when the pressure changes take place rapidly the sense of their isolation is lost and they blend into a musical note. This point represents the lower limit to the ear's powers of analysis and occurs at about 16 cycles per second; the upper limit occurs at approximately 20,000 cycles per second; middle C on the piano is 256 cycles per second.

It is sometimes useful to be able to estimate quickly the natural frequency of a column of gas in a certain length of pipe of constant cross-section. Fig. 4 enables this to be done for air at 20° C. and at 370° C. The error owing to the differences in composition between air and exhaust gas is sufficiently small for a first order estimate to be made, but for a more accurate estimate the frequency obtained from the graph should be multiplied by $\beta$

$$\text{where } \beta = \sqrt{\frac{\gamma_e \rho_a}{\gamma_a \rho_e}}$$

$$\text{and } \gamma_e = \frac{\text{sp.ht. at constant pressure for gas}}{\text{,, \quad ,, \quad ,, \quad volume \quad ,, \quad ,,}}$$

and $\gamma_a$ = similar quantity for air

$\rho_e\ \rho_a$ = density of gas and air respectively.

For frequencies and lengths not covered by the graphs,

$$f = \frac{c}{4l}$$

where f = natural frequency in fundamental mode, cycles/min.

c = speed of sound in medium, feet/min.

l = length of pipe in feet; one end open, one end closed

$$\text{also } c = \sqrt{\frac{\gamma P}{\rho}}$$

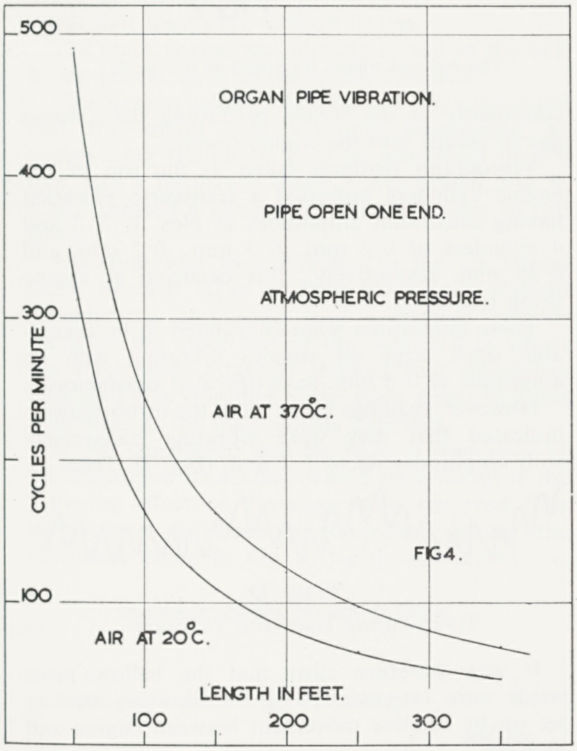
where $\gamma$ = ratio of specific heats

P = mean pressure

$\rho$ = density

for air at 20° C.; c = 1,100 feet/sec.

These equations are reasonably accurate for pipes above 10 in. diameter.

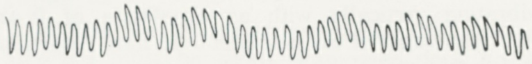



**Transverse Vibration of Main Engines in Motor Ships**

EXAMPLE 3

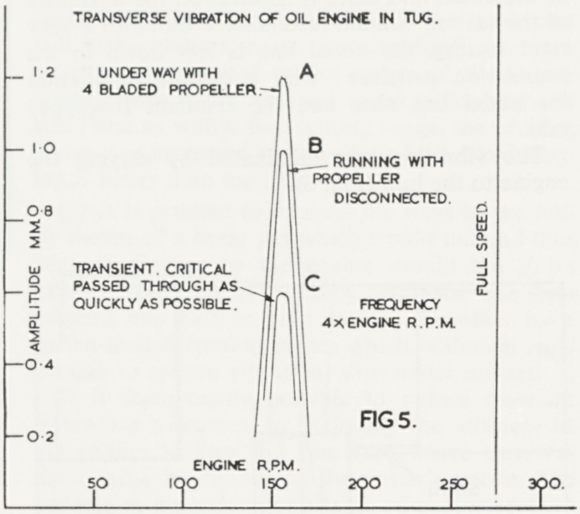
An eight-cylinder, single-acting four-stroke engine was installed in a tug fitted with a four-bladed propeller.

The engine vibrated excessively in the transverse mode and the resonance curve A (Fig. 5) was drawn from Askania readings taken from the cylinders, Trace C. Since the frequency was 4 × engine revolutions per minute, the propeller shaft was disconnected in order to confirm that the vibration was excited by the engine and not the propeller; the resonance curve B (Fig. 5) was obtained.

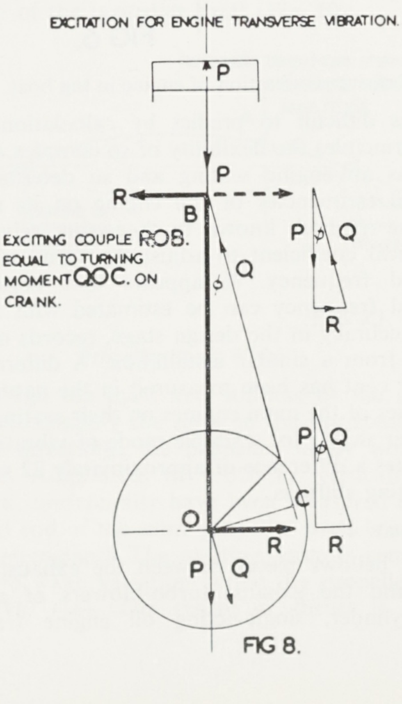


Trace C

Transverse Vibration. Engine Cylinders




It will be seen that the reduction in amplitude when the engine was running light was relatively small, approximately 17 per cent. Torque reaction arising from cylinder gas force and inertia force usually provides the exciting force for this type of vibration (Fig. 8). Torque variation at the propeller can affect the exciting force, increasing or decreasing it according to the phase relation between the propeller and crankshaft, but in this example the propeller excitation appeared to be small, and the reduction in amplitude to be caused by reduction in gas force when running light.



In addition to the engine itself, the seating was vibrating vertically with an amplitude of 0·45 mm., the edges of the bedplate 0·35 mm. vertically and horizontally, and the deep frame 0·5 mm. vertically. A strong impression was received that the mass of the hull was vibrating against the engine mass with the nodal line passing approximately through the centre of the crankshaft journals (Fig. 6). This is not always the position of the nodal line, since it depends on the flexibility of the seating. Should resonance occur with a very rigid seating, the nodal line is low down in the foundation structure; with a flexible foundation the nodal line rises and the resonant frequency falls.

The vibration was eliminated by staying the engine to the hull (Fig. 6).

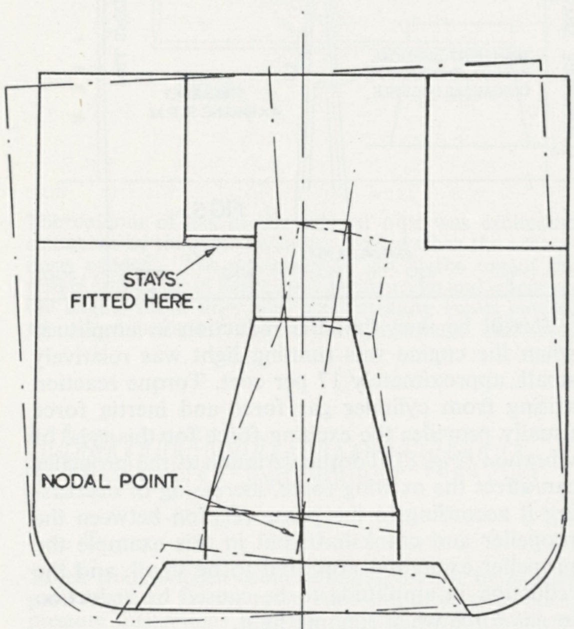



FIG 6.

Transverse vibration of engine in tug boat

It is difficult to predict by calculations from first principles the flexibility of so complex a structure as an engine seating and so determine the natural frequencies of the engine on its seating. All the methods known to the writer rely on an empirical coefficient to adjust the value of a calculated frequency. It appears that before the natural frequency can be estimated with reasonable accuracy in the design stage, records must be taken from a similar installation. A difference of 11 per cent has been measured in the natural frequencies of the main engines on their seatings even in sister ships; for a simple mode of vibration this indicates a difference of approximately 22 per cent in seating stiffness.

EXAMPLE 4

The bellows pieces between the exhaust manifold and the exhaust turbo-blowers of a large four-cylinder, single-acting oil engine fractured

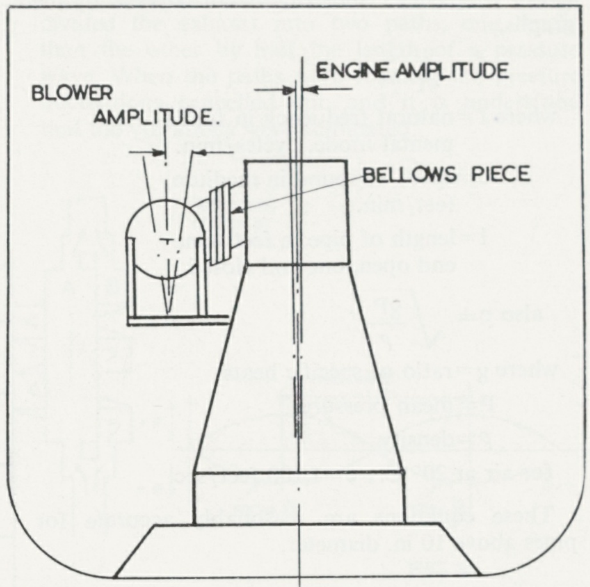



FIG 7.

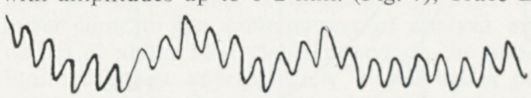
The bellows pieces fractured at the welds

continually at the welds, permitting the exhaust gas to escape into the engine room.

Vibrograph readings taken at the top of the engine cylinders indicated a transverse vibration having maximum amplitudes at Nos. 1, 2, 3 and 4 cylinders of 0·2 mm., 0·3 mm., 0·2 mm. and 0·25 mm. respectively; this occurred at engine firing frequency.

These amplitudes were considered to be acceptable since large oil engines vibrating with an amplitude of 0·5 mm. have operated satisfactorily.

However, readings taken from the turbo-blowers indicated that they were vibrating transversely with amplitudes up to 1·2 mm. (Fig. 7), Trace D.



Trace D

Turbo-Blower Transverse Vibration

It was therefore clear that the bellows-piece welds were fatiguing owing to vibratory stresses set up by relative movement between engine and blowers.

This defect, although cured relatively easily by stiffening the blower supports to the engine, is important in that it illustrates that vibration of small amplitude and low frequency can cause damage if it results in one large mass of the engine moving relative to another. Fractures in the casting between adjacent cylinders and in the columns have occurred owing to transverse vibration. When fitting stays between the engine and hull it is essential that they should be attached to the hull at equally rigid points, otherwise the engine will be restrained more at one point than another and vibratory stresses will be set up in its structure.

In this case, stiffening the engine seating or fitting stays between the cylinders and hull would have done more harm than good since, while reducing the amplitude of the engine, it is unlikely that it would have affected the amplitude of the blowers. These were vibrating on their supports as separate systems, the exciting force being supplied when the engine moved.

Reduction in engine movement does not necessarily bring about a corresponding reduction in the amplitude of this type of system; the amplitude appears to be limited mainly by a sudden increase in support stiffness when it, the amplitude, reaches a certain value.

Example 5

A large five-cylinder two-stroke cycle engine vibrated transversely at full speed to such an extent that certain copper pipes and welded connections appeared likely to fail.

In the accommodation, the vibration was uncomfortable and annoying, and on the bridge many of the navigating instruments vibrated so much that they were difficult to use.

The main engine was already stayed to the hull by six lateral stays of heavy cross-section.

Vibrographs taken from the cylinders indicated that the engine was vibrating transversely at engine-firing frequency with an amplitude of 0·8 mm. and a resonance curve A was drawn, Fig. 9, which showed a clearly defined peak close to full power.

Attention was then directed to the six lateral stays. Records taken at their outer ends showed considerable amplitude, and additional records taken on the other side of the bulkhead to which the stays were attached showed that the entire bulkhead was vibrating at the same frequency and amplitude as the main engine cylinders.

It was considered that the natural frequency of the engine on its seating would be reduced if the stiffening effect of the stays were removed. The stays were therefore disconnected, giving the resonance curve B, Fig. 9, which was acceptable.

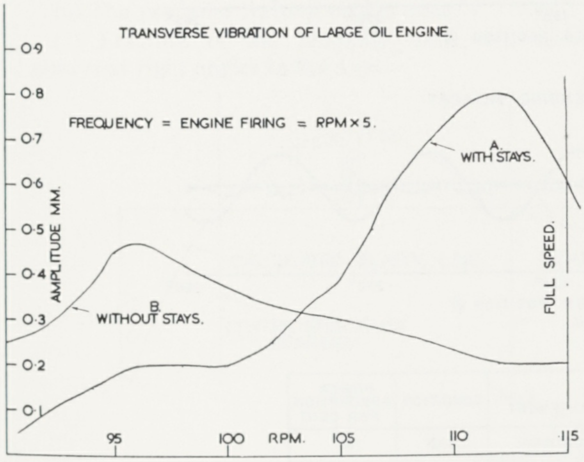



Fig. 9

No stiffening is better than too little

Experience indicates that when staying a main engine: —

(1) The part of the hull to which the stays are attached must be rigid. Transverse deck beams are usually suitable.

(2) Care must be taken that sufficient stiffness is added to raise the resonant frequency at least 10 per cent above the running speed. It is usually easier to deal with a resonance which occurs at full speed than one which occurs at, say, three-quarter speed, since insufficient stiffening in the latter case will make matters worse. Exciting forces are very roughly proportional to the square of the engine speed, hence if the resonant speed is doubled and still remains within the running range, the exciting forces are increased roughly four-fold. No stiffening is better than too little.

(3) It is prudent to connect the stays to the hull by means of a shear pin which would fail and thus prevent damage to the engine should the ship's side be distorted by collision. At least one firm connect one half of each stay to the other by a spring-loaded friction device which, although rigid enough to reduce vibration, slips under impact.

It is theoretically possible to reduce resonant transverse vibration by reducing the stiffness of the engine seating and one case where this was done came by chance to the writer's notice. The welding in the seating of a large oil engine cracked slightly owing to transverse vibration and to overcome this the seating was stiffened. It then cracked extensively. The stiffening was removed and the plates where the original cracks occurred were cut away. No further cracks appeared. It would appear that the engine seating was incorrectly designed in the first place, but as the vessel was not classed with the Society, details were not available.

**Propeller Shaft Whirl**

In this type of vibration the propeller whirls on the end of the propeller shaft (Fig. 10).

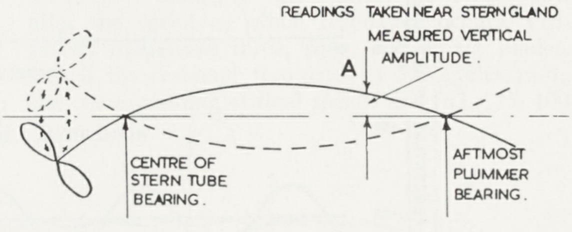



FIG IO.

Propeller Shaft Whirl

Although the mass and stiffness of the system are approximately the same in the horizontal and vertical directions, the propeller rarely whirls in a circle. Amplitudes of 0·026 in. vertically and 0·016 in. horizontally have been measured on the forward end of the same propeller shaft liner near to the sterngland. The exciting force is generated owing to wake variation across the propeller disc (Figs. 11, 11a). The centre of thrust is rarely

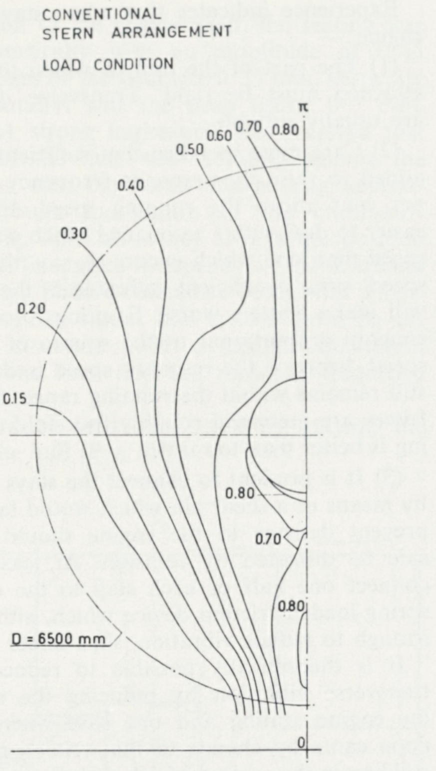



Fig. 11

Wake Plot, ref. 8

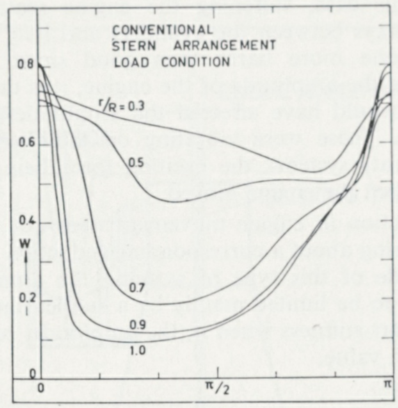



Fig. 11a

Circumferential Wake Distribution, ref. 8

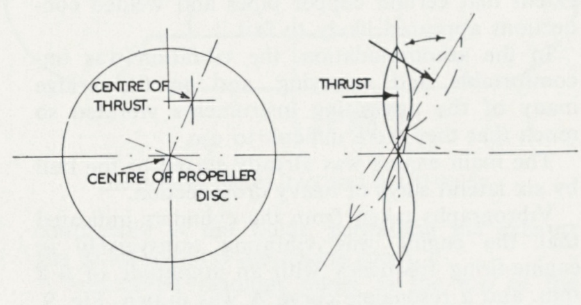
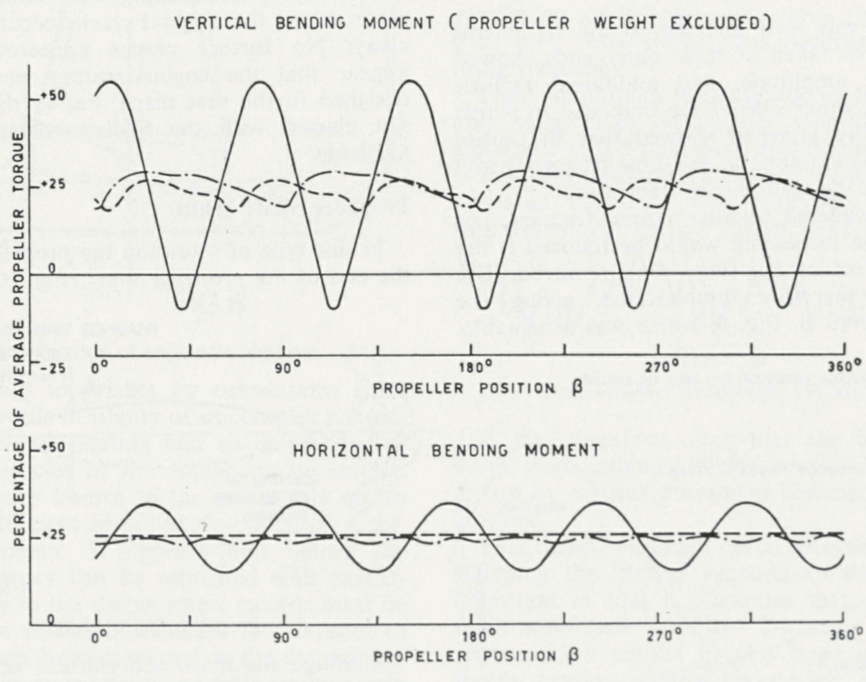



Fig. 11b




| INDICATION | PROP. | NUMBER OF BLADES | STERN ARRANGEMENT | CONDITION | POWER ABSORPTION PER CENT |
|---|---|---|---|---|---|
| ———— | II | 5 | CONVENTIONAL | LOAD | 100 |
| — — — — | V | 6 | CONVENTIONAL | LOAD | 100 |
| —·—·— | VI | 4 | CONVENTIONAL | LOAD | 100 |

Fig. 11c, ref. 8

located at the centre of the disc and a moment of thrust therefore exists about the diameter at right angles to the line passing through the centre of thrust and the centre of the disc (Fig. 11b). Since the vertical component of this moment is usually greater than the horizontal (Fig. 11c) the propeller whirls in an ellipse with the major axis practically vertical.

This type of vibration is characterised by one or more of the following: —

(1) Rapid weardown of the lignum vitae in the stern tube bearing (up to 3 mm. in three months). The wood in the bottom of the stern tube is hammered rather than worn for some distance from the aft end.

(2) A wear pattern on the propeller shaft liner as in Fig. 12. The location of the polished bearing surfaces changes with different vessels and they are sometimes absent altogether, but it is usually possible to see the eroded patches. These often consist of a large number of circumferential grooves which are caused by the high speed movement of the water passing from the top to the bottom of the bearing and back again each time the shaft vibrates.

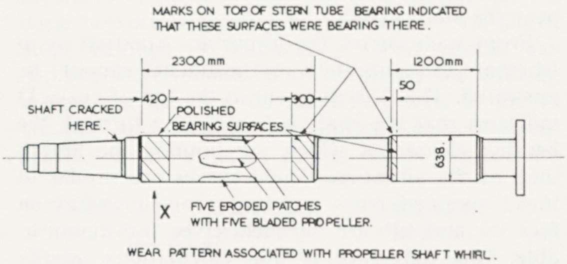



Fig. 12

(3) Difficulty in keeping the sterngland reasonably watertight; jets of water issue from the gland and may travel along the tunnel for ten or twelve feet.

(4) Hammering out of the white metal in the aft-most plummer bearing in either the top or bottom half, or both.

(5) The propeller nut becoming slack.

(6) The propeller fretting on the cone.

(7) Fracture of the propeller shaft, but not always at right angles to the axis.

(8) Fracture of the bottom of stern tube at the aft end.

(9) Fracture of stern frame welding in way of the stern tube.

(10) Loosening of aft-most plummer bearing holding-down bolts.

(11) Usually occurring between 75 per cent and full speed.

Propeller whirl arises from two different types of vibration which, although very similar, do not respond equally well to the same treatment. They are: —

(*a*) Resonant Propeller Whirl.

(*b*) Forced Propeller Whirl.

(*a*) Resonant Propeller Whirl, occurs when the propeller blade frequency coincides with the natural frequency of the propeller on the end of the shafting. The natural frequency may be estimated by the method given by Panagopulos (Ref. 5), or by calculating the elastic line of the shafting and applying the formula, $N = 187 \cdot 7 \sqrt{\frac{\Sigma wy}{\Sigma wy^2}}$

where w is the weight of discrete sections along the shafting and y their deflections. Fig. 13 compares the calculated elastic line with amplitudes measured on the shafting of a large tanker at approximately 100 r.p.m. The estimated critical speed was 120 r.p.m.

If the vertical amplitude of the shafting measured at A (Fig. 10) is plotted against shaft revolutions per minute, resonant whirl gives a curve similar to either A or B, Fig. 14. Curve A shows a clearly defined resonance, the maximum amplitude of which is limited by the clearance of the shafting in the sterntube and aft-most plummer bearing; its main purpose is to define the speed range over which the vibration is severe, confirm that the vibration is resonant, and give the resonant frequency.

Since the vibration is excited at propeller blade frequency, changing the number of blades will alter the speed at which resonance occurs. Propellers may have three, four, five or six blades, and if the resonant frequency is 500 cycles/min., the corresponding critical speeds are 167, 125, 100

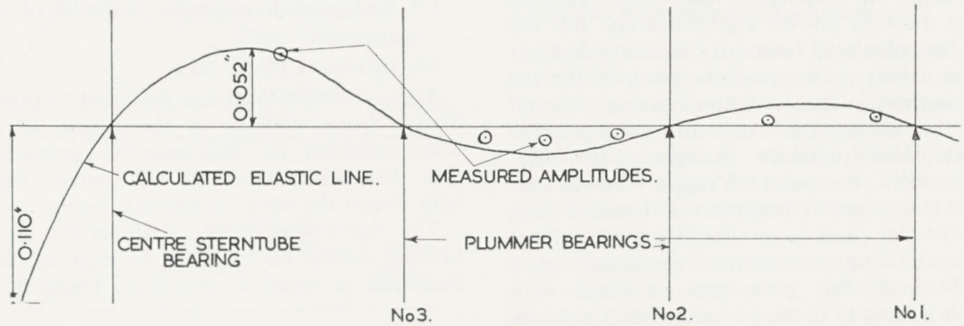
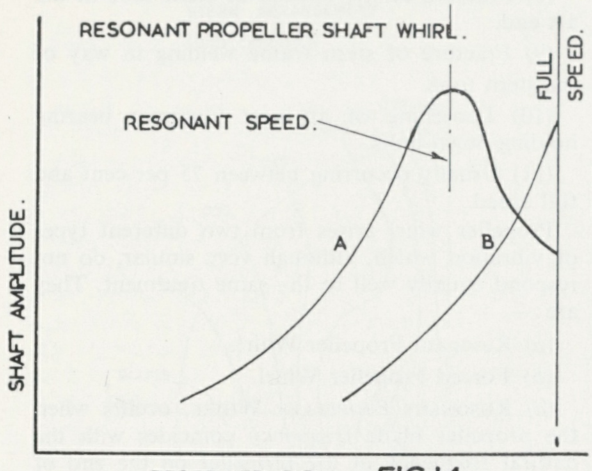



Fig. 13

Propeller Shaft Whirl

Comparison of calculated elastic line with amplitudes measured on the shafting of a large tanker at approximately 100 r.p.m. Estimated critical speed 120 r.p.m.

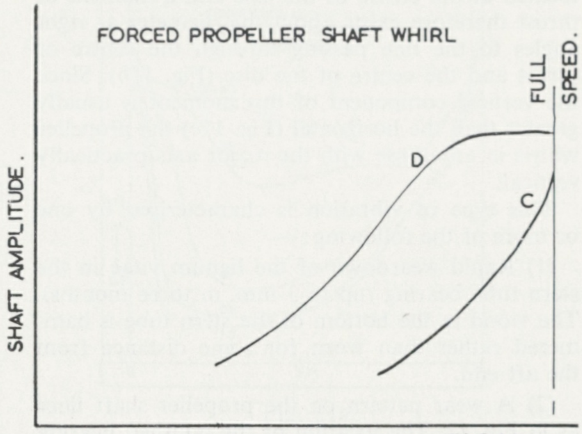



PROPELLER R.P.M. **FIG 14**

and 83 r.p.m., respectively. It might be thought that, for resonant propeller whirl, changing the number of blades and so removing the critical speed from the running range would reduce the vibration, but this it not necessarily so.

Fig. 11c shows the variation in vertical and horizontal bending moments, i.e., excitation, exerted by four, five and six-bladed propellers. It will be seen that owing to its relatively large vertical bending moment, although changing from a five-blader to a four or six would probably eliminate resonant propeller whirl, changing from a four or six to a five could cause forced propeller whirl. The vertical bending moment caused by eccentric thrust from a five-blader can be much greater than that caused by its weight, with the result that the propeller shaft lifts through its bearing clearance.

Curve B (Fig. 14) gives only the flank of the resonance curve, from which it is not possible to determine the resonant frequency and hence the new critical speed for a change in the number of blades. It may be inferred from such a curve that decreasing the number of blades will place the critical speed further above full speed (which is probably desirable) while increasing the number of blades might bring the critical nearer to full speed. Hence, before it can be decided whether or not to change the number of blades, the resonant frequency must be known approximately. But the value of the calculated resonant frequency depends to a large extent on the position assumed for the point of support in the stern tube bearing. A small error in this assumption can cause a large error in the calculated frequency; further, as the bearing wears down, the point of support moves forward and the resonant frequency is lowered. The selection of the position of the point of support from the drawing is therefore something of a guess. However, this guess can be made with reasonable accuracy if the propeller shaft exhibits a wear pattern as in Fig. 12, since then the point of support may be taken as half way along the aft bearing surface at X. The resonant frequency can then be calculated and a decision taken concerning the number of blades.




Propeller r.p.m. **FIG 15.**

(*b*) FORCED PROPELLER WHIRL occurs when the variation in the moment of thrust is large enough to lift the propeller and shaft in the stern tube each time a blade passes the stern frame.

Fig. 15 shows the types of curves which may be obtained from readings taken from the shafting near the stern gland.

From such curves the important question as to whether the vibration is resonant cannot be answered. The flattening out at the top of curve D indicates that the shaft is hammering through the bearing clearances which are limiting the amplitude of the vibration. These curves are similar to those obtained from resonant propeller whirl, in fact 15c and 14b are, by themselves, indistinguishable. One difference is that calculations usually indicate that the resonant frequency is remote from the forcing frequency with forced propeller whirl; another, and more important one, is that changing the number of propeller blades does not necessarily eliminate forced propeller whirl. If a five-bladed propeller is forcing the vibration, changing to one with six blades will probably give a greater reduction than one with four. Slight reduction in excitation for any propeller will probably be accomplished by:—

(1) Pitch reduction towards the tips.

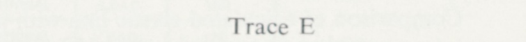
(2) Reduction in area towards the tips.

(3) Reduction in propeller diameter of up to 10 per cent.

(4) Increased blade rake.

These modifications are designed to prevent the blades from working in the region of greatest wake variation, i.e., that near the perimeter of the disc. Increased skewback will reduce the shock with which the blade enters this region.

The movement of the shaft in the stern tube bearing should be restricted by making the initial clearance as small as practical, Traces E and F.



Trace E

Propeller Shaft Whirl. Worn Lignum Vitae

Trace F

Lignum Vitae Renewed

The rate of weardown should be reduced as far as possible, and one method sometimes advocated for this is to fit a metal stern tube bearing with oil glands.

Where lignum vitae is fitted, 1 mm. is sufficient initial clearance for a large (640 mm.) diameter shaft and it is claimed that a reduction in the rate of weardown can be obtained by boring the stern-tube at the slope corresponding to the line of the propeller shaft in service. This slope can be estimated by first calculating the values of bending moments at points of support of the shafting by Clapeyron's theorem of three moments, and then drawing the bending moment diagram and integrating graphically. (Macaulay's method of integration gives rise to very large numbers which can be the cause of inaccuracies since it is upon their differences, often small, that the result depends.) It appears that the estimated slope for large tankers is usually of the order ·010 in./ft. Slope through A brackets in naval vessels was checked experimentally by removing the bearing bushes and jacking the shaft at points in the A bracket and taking appropriate measurements. Sloping the A bracket to the elastic line of the

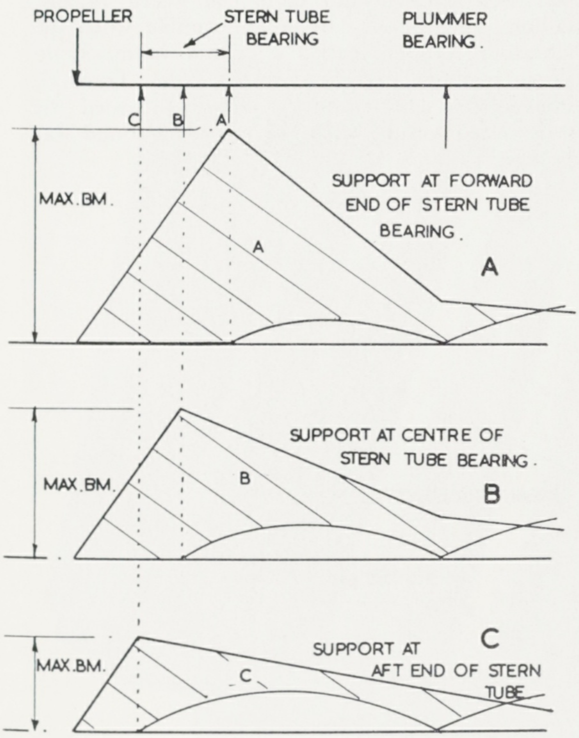



FIG 16.

Simplified Static Bending Moment Diagrams

The bending moment on the shaft increases as the point of support in the sterntube moves forward and away from the propeller

shafting prevented the rapid wear of the rubber bearings initially experienced.

The slope-bore method does appear to equalise the bearing pressure along the stern tube, but at the expense of increased bending stress in the shaft as shown by the simplified bending moment diagrams in Fig. 16 a, b and c. Figs 16d and 16e indicate the reason propeller whirl tends to fatigue the shaft at the large end of the cone.

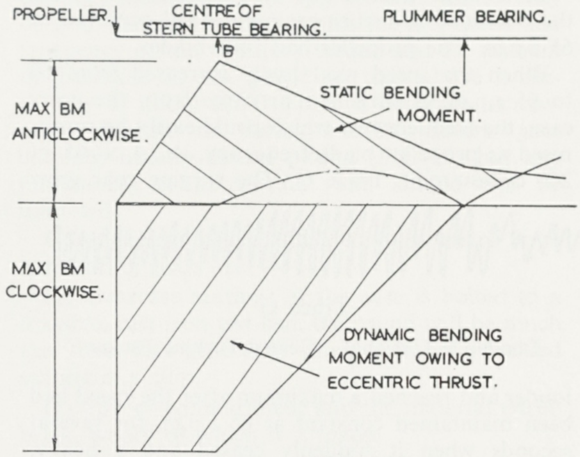



FIG 16D.

Simplified Bending Moment Diagrams

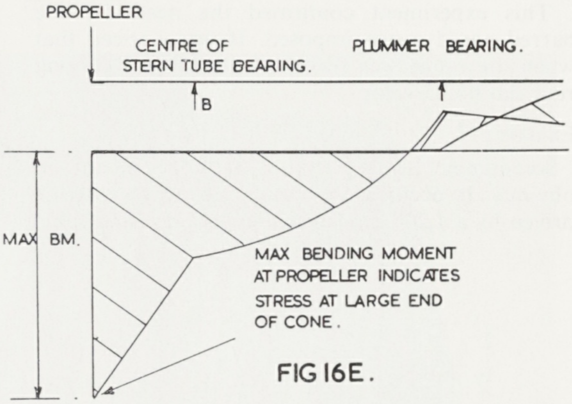



FIG 16E.

Combined Static and Dynamic Bending Moment Diagrams

**Torsional Vibration in Machinery**

The torsional vibration characteristics of the main and auxiliary heavy oil engines are studied by the Society before a vessel is classed. Where critical speeds are found by calculation to occur within the range of working speeds, the Committee may require torsiograph records to be taken from the machinery for the purpose of verifying the calculations and may impose a restriction on continuous running at speeds where the vibration torques, as evidenced by tooth separation and gear hammer in geared drives, or by stresses derived from records, are considered to be excessive.

The interpretation of torsiograph records is a specialised art, discussion of which would be out of place in general notes on vibration such as

these; hence this section is limited to a description of symptoms of torsional vibration which the writer has noticed when taking torsiographs. Brief comments are also made on typical dampers and detuners.

**Gear Hammer**

EXAMPLE 6

In a large geared turbine tanker installation, the one-node propeller excited critical occurred at 65 r.p.m. The propeller had four blades.

When the speed was slowly increased from 60 to 65 r.p.m., a surging roar came from the gearcase, the frequency of which could easily be recognised as propeller blade frequency, i.e., $4 \times 65 = 260$ cycles/min., Trace G. The surging roar grew

Trace G

One-Node Torsional. Geared Turbine Tanker

louder and reached a maximum after the speed had been maintained constant at 65 r.p.m. for several seconds when it suddenly ceased and a heavy, intermittent rumbling occurred; the gearcase, turbines and steam piping vibrated. The gears were hammering.

This experiment confirmed the need for the barred speed range imposed. It was noticed that when the range was traversed quickly the surging roar did not develop.

EXAMPLE 7

Sometimes, however, gear hammer is not so obvious. It occurred in double reduction gearing driven by a 1,200 h.p. sixteen-cylinder, four-stroke, single-acting oil engine when the engine and gearing were on the test bed.

The frequency of the vibration was approximately 3,000 cycles per minute and the rig was so instrumented that it was possible to learn in a few seconds when the vibratory torque exceeded the transmitted torque.

By watching the instruments and listening to the gearcase with a stethoscope or a wooden-handled screwdriver, a comparison could be made of the sound emitted with and without gear hammer. The difference, although quite marked when the listener knew what to listen for, was not great enough to be used as a criterion for gear hammer, even when the hammering was severe (Fig. 17). The difference lay in the timbre of the sound rather than its loudness. The installation was not classed with the Society.

EXAMPLE 8

This concerns two eight-cylinder, four-stroke, single-acting engines driving into a single-reduction gearcase through slip couplings.

Each coupling slipped by a different amount so that the relative phase of the crankshafts, and hence exciting forces, changed continually. Owing to deterioration of the dampers, torsional vibration with gear hammer occurred at a certain speed whenever the exciting forces were in phase. The vibration frequency was 1,100 cycles per minute. The noise usually associated with torque surge was well defined and could be heard in the saloon; it gave way to pinion rumble when the vibratory torque reached a certain value. Strain gauge readings from the pinion shafts, Trace H, showed that the vibratory torque exceeded the transmitted torque when the rumbling sound was emitted.

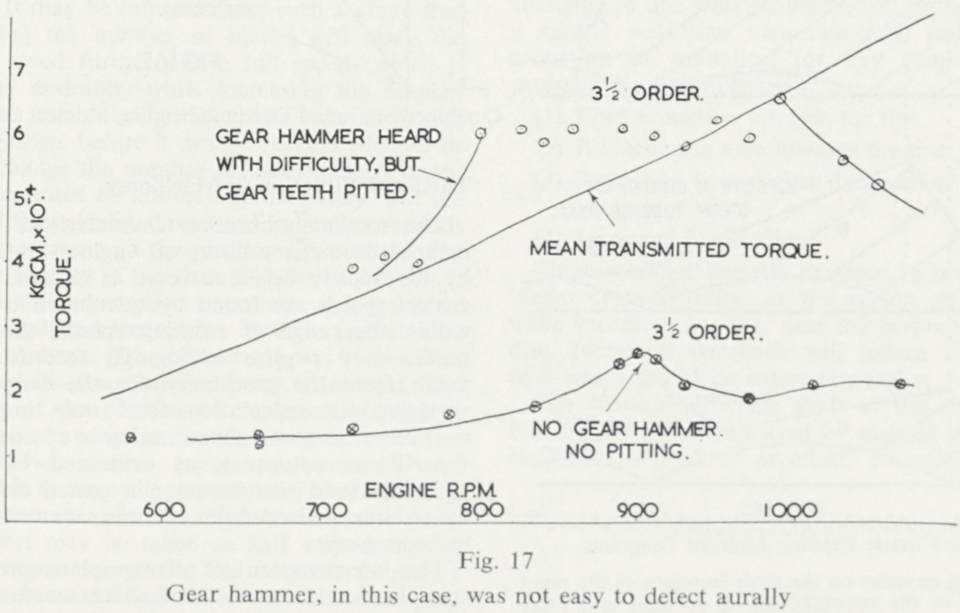
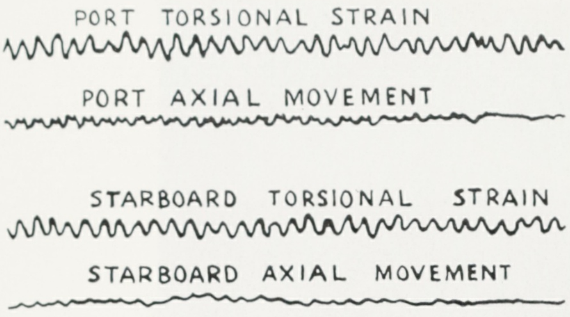



Fig. 17

Gear hammer, in this case, was not easy to detect aurally




Trace H

These strain gauge records show clearly axial movement of pinions and torsional vibration in the pinion shafts occurring simultaneously. The gear teeth were in a poor condition

EXAMPLE 9

The crown wheel and pinion of an installation consisting of a four-cylinder two-stroke engine driving a Voith-Schneider propeller, hammered violently when the engine was started. The noise was literally deafening and continued from starting up to about 360 r.p.m. when it disappeared. Normal speed was constant at approximately 400 r.p.m. and the speed of the boat was varied by the amount of pitch on the propeller. Gear hammer can easily occur at critical speeds with installations having variable pitch propellers since it is possible to run the gears with negligible transmitted torque, i.e., no pitch on the propellers. Gear hammer then takes place over a wide speed range. Figs. 18 and 18a show a pinion damaged by this type of gear hammer.

It will be seen from the above examples that the noise emitted when gears hammer varies in different installations. It appears that the severity of gear hammer increases with the amplitude and frequency of the vibratory torque and the amount of backlash in the gear, but that above a frequency of about 2,500 c.p.m. it becomes increasingly difficult to detect aurally. Severe gear hammer usually causes pitting (Fig. 19) but any hammering is detrimental and should not be tolerated.

Other factors which affect the noise heard from hammering gears are:—

(1) Gearcase seating: if the case is bolted to a massive, cast iron test bed, the sound will be much less than that generated when it is on a welded seating in a ship.

(2) Size of compartment and the material (steel, brick, wood) of which it is made.

(3) Background noise; the prime mover will sometimes drown the noise of gear hammer, especially if hammering occurs at engine firing frequency.

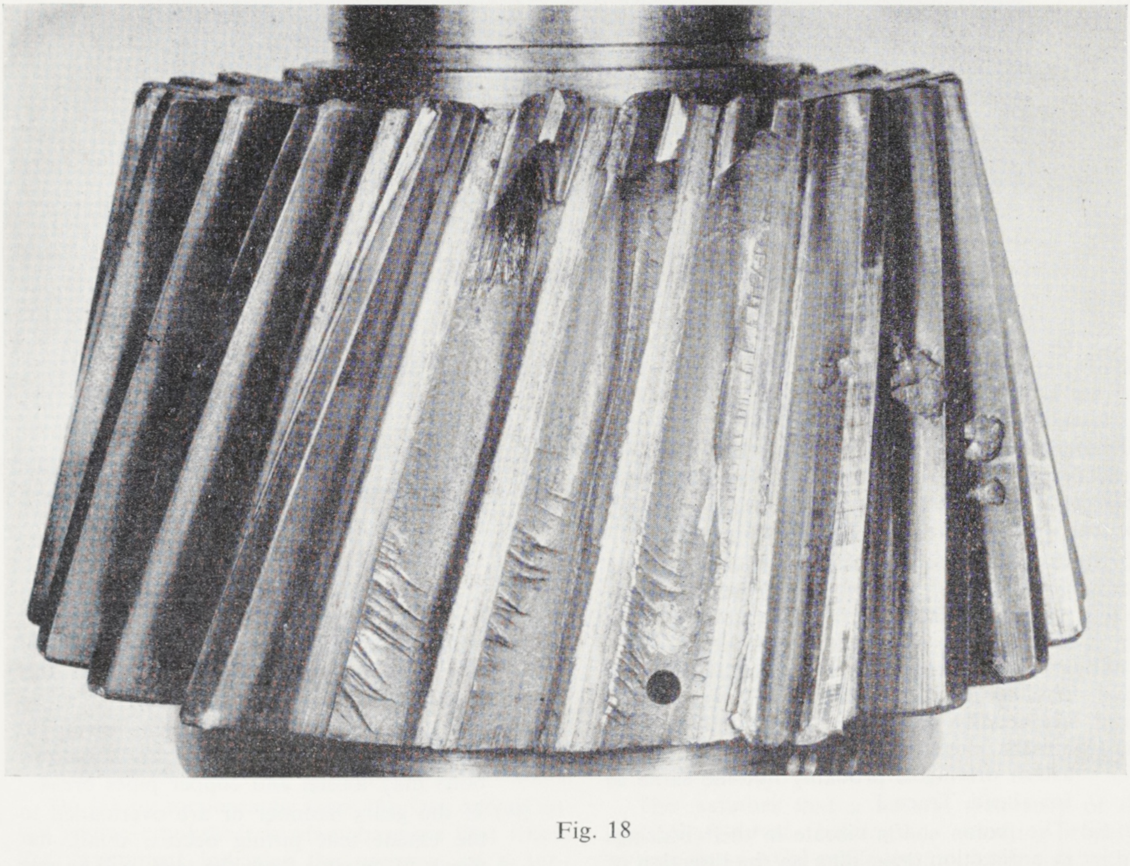


Fig. 18

Pinion damaged by gear hammer generated by torsional vibration

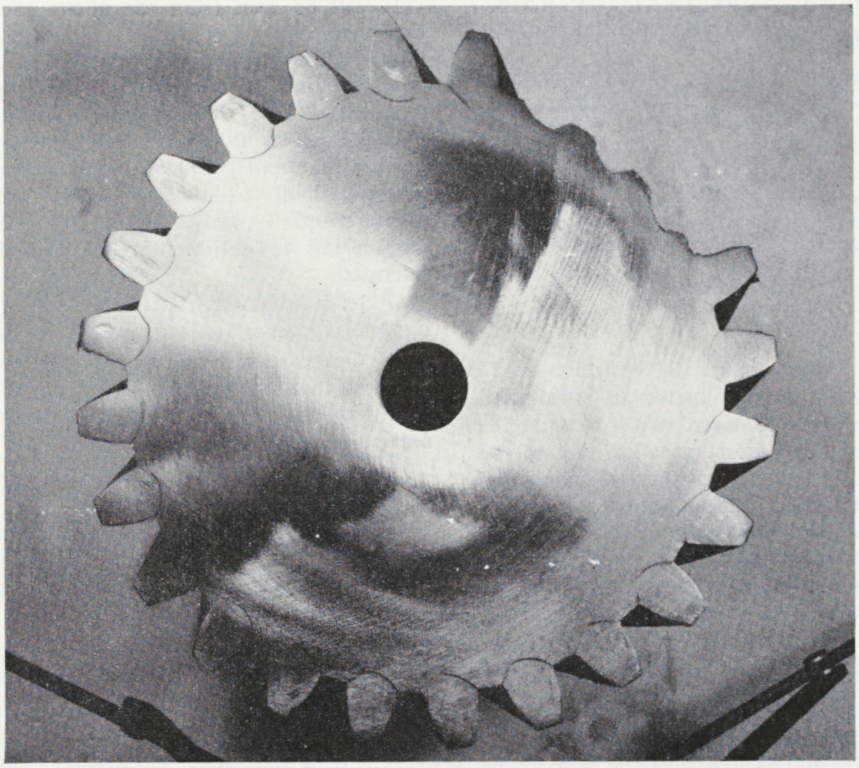


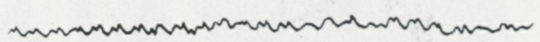
Fig. 18a

Section showing cracks at roots of teeth

If there is doubt whether or not gear hammer is occurring, and no instruments are readily available, a fairly reliable indication of high vibratory torques may be given by the following:—

(i) If the gears are single helical and the pinions are axially free, when torque reversal takes place the pinions vibrate axially with a maximum amplitude equal to the axial clearance of the thrust bearings. If gears are double helical and the pinions are axially free, they might still vibrate axially, since the equilibrium position for astern driving is probably not the same as for ahead, Trace J.

(ii) The pinion shafts vibrate in their bearings in a direction depending on the direction of the torque reaction when torque reversal takes place (Fig. 20). Hammering out of white metal has been attributed to this action.



Trace J

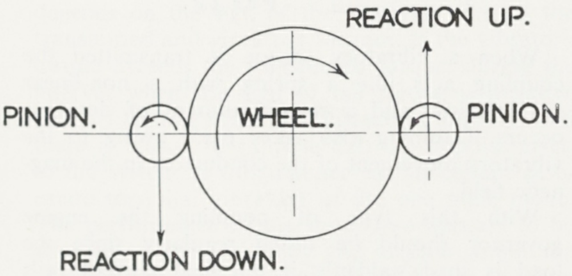
Torsional Induced Pinion Axial

(ii) The gearcase itself may vibrate owing to vibratory torque reaction; holding-down bolts may loosen and copper pipes break.

(iv) If the gears hammer or are overloaded to the extent that pitting occurs, small, flat pieces of detritus from the teeth will appear in the magnetic filters.

Fig. 19

Banded pitting of teeth caused by torsional vibration




PINIONS VIBRATE VERTICALLY UNDER HIGH VIBRATORY TORQUES.

FIG.20

**Indications of Torsional Vibration in Oil Engines**

On taking torsiographs from the free end of an oil engine crankshaft it often happens that when the instrument indicates the presence of a torsional critical, the instrument pulley attached to the end of the crankshaft vibrates axially. On the occasions when the writer has measured the frequency of this axial with a hand vibrograph, it has always occurred at the same frequency as the torsional. Sometimes, however, a torsional vibration occurs with very little axial movement of the free end of the crankshaft.

It appears that the axial movement is caused by a shortening of the crankshaft when it is twisted by vibratory torque. Hence this shortening will be greatest for torsional modes with a node in the crankshaft. Conversely, if the mode of vibration is such that the crankshaft has relatively large angular amplitudes, with the node in the intermediate shafting, the shortening of the crankshaft will, if evident at all, be small.

This assumes that a natural frequency of the crankshaft-thrust bearing-line shafting-propeller system in an axial mode does not coincide with a natural frequency in the torsional mode. When

this occurs the amount of vibratory energy stored is more than with a simple torsional or axial. This energy twists the shaft at the same time as it extends it and the resulting stresses can be dangerous.

The writer measured an axial vibration of 2·0 mm. amplitude at the free end of the crankshaft of a large eight-cylinder four-stroke oil engine; i.e., total movement of 4·0 mm. This occurred at 56 r.p.m., which was a torsional critical speed. In this case the axial clearance on the thrust collars was excessive, 3·3 mm. Apparently the axial was generated by the torsional.

Torsional criticals severe enough to force an axial in the crankshaft are nearly always accompanied by harsh and noisy running of the engine, one of the more distinctive noises sometimes heard is camshaft driving chain rattle. Other signs are broken copper pipes, excessive wear in valve gear and other components, and fractured welding in what would normally be a lightly stressed part. In one large direct coupled engine a crack started at the top of the plate enclosing the aft end of the crankcase and extended downwards for about 2 ft.

Although it is known that certain torsionals might induce axials, apparently the converse does not apply. This is not surprising when it is considered that although a body, a piece of rubber for example, may be shortened by twisting it, when it is extended or compressed there appears to be no inducement for it to twist. An axial vibration at the end of a crankshaft is not, therefore, an infallible indication of a torsional vibration, since an axial may occur by itself.

**Torsional Vibration Dampers and Detuners**

A Vibration Damper is a device for removing the energy put into the system by the exciting force, this energy would otherwise appear as strain energy in members under vibratory stress, i.e., at nodes, and as kinetic energy in the vibrating masses, i.e., at antinodes.

Dampers of the Holset type (Fig. 21), which depend on the resistance offered by a viscous

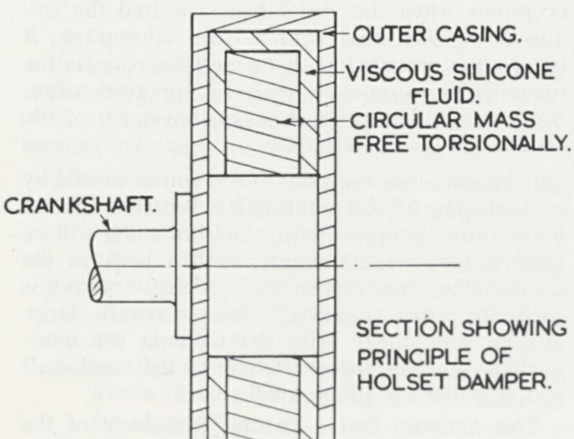



FIG 21.

silicone fluid when it is sheared by the relative motion of the vibrating outer casing and the mass, are most effective when they are located at an antinode, and are commonly placed at the free end of an oil engine crankshaft. Since the amplitude at this point may differ with different modes of vibration, the damper may be more effective for one mode than for another. In certain geared turbine installations propeller damping is usually greater for a one-node torsional where the node is remote from the propeller than for a two-node where there is a node near to the propeller.

A Vibration Detuner is a device which automatically changes the natural frequency of a vibrating system when resonance is approached and so prevents the building up of large amplitudes. Detuners may be fitted at nodes or antinodes, depending on their principle of operation.

Most devices for the elimination of torsional vibration employ both damping and detuning as in the following examples.

(i) Magnetic Slip Coupling

This device (Fig. 22) is fitted between engine and gear box. The poles are magnetised and when the driving half rotates the conductors cut the lines of force and the driven half is dragged round.

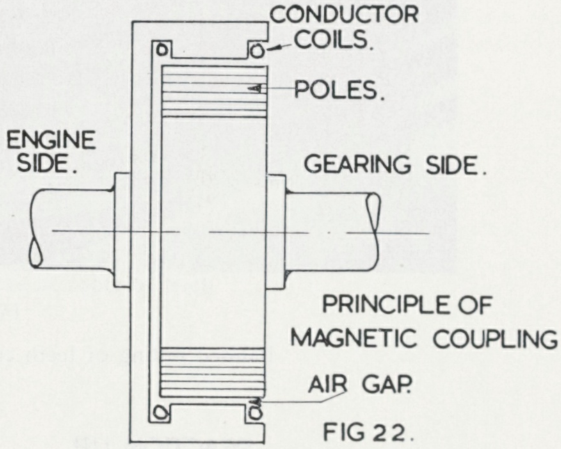


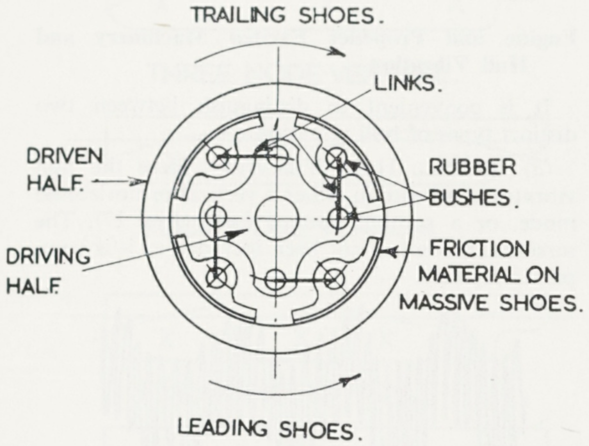

FIG 22.

When a vibratory torque is transmitted the coupling acts like a spring with a non-linear characteristic and a certain amount of detuning occurs. Damping also takes place owing to the vibratory movement of the conductors in the magnetic field.

With this type of coupling the engine governor should be tested regularly since the load is shed suddenly if the field current fails and if, in addition, the governor sticks, excessively high speeds can be reached. A second point is that the air gap between poles and conductors should also be checked regularly, preferably with a wedge gauge. Weardown in the bearings of the driven member increases the load on those bearings; the air gap at the bottom of the coupling is reduced, which results in an out of balance magnetic force tending to pull the driven member down and lift the driving.

(ii) Centrifugal Friction Coupling

This device (Fig. 23) is also fitted between the engine and gearing. When the driver reaches a certain speed the centrifugal force on the shoes overcomes the torque in the rubber bushes and the friction element contacts the driven member and drags it round. It is sometimes possible to select the engaging speed so that it occurs above dangerous criticals.




PRINCIPLE OF ONE TYPE OF CENTRIFUGAL COUPLING.

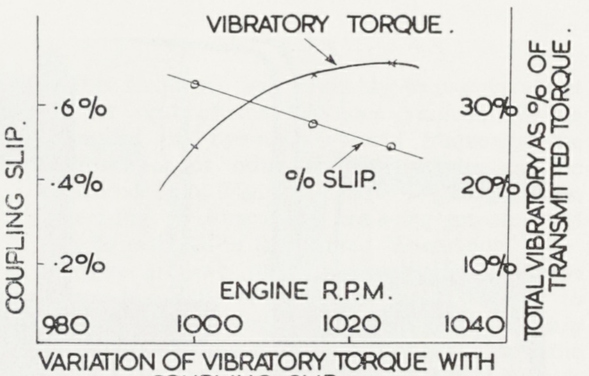
Fig. 23

At full load the shoes inch round with a low slip. If vibratory torque is super-imposed on the transmitted torque the slip increases to about 2 per cent and detuning occurs; a certain amount of damping may also take place. The effectiveness of the coupling depends to a large extent on the co-efficient of friction betweeen the shoes and the drum, and also on the angle between the centre line of the link (produced) and the tangent to the drum. On the coupling shown the shoes may lead or trail, depending on the direction of rotation, hence the torque at which the coupling slips depends on the sign of the algebraic sum of the transmitted and vibratory torques. If the vibratory torque exceeds the transmitted torque, during the interval when the sign of the torque is negative (astern) leading shoes bite instead of slipping, and there is reason to suppose that the impulse given to the system in this manner can in certain cases excite torsional vibration in the one node mode. The performance of the shoes also appears to be affected by the frequency and angular amplitude of the point in the system at which the coupling is fitted. Clearly a coupling which depends on rotational speed for its performance will respond to fluctuations in that rotational speed.

It is a matter for speculation whether or not dry friction as employed in couplings of this type is entirely desirable. Of course there are installations containing these couplings which are working satisfactorily, but dry friction has the characteristic that its friction force is greater for small slipping velocities than for large ones. This property is completely opposite to that of viscous friction. Suppose the absolute velocity of the shoe is always greater than the absolute vibrating velocity of the driven half so that the direction of slipping is always the same; while the shoe is moving in the direction of the driven half, the slipping velocity is small, and consequently the friction force is great, but while the driven half vibrates in the opposite direction the slipping velocity is large and the friction small.

Since the large friction force acts in the direction of motion of the driven half it appears that the work done by friction over a full cycle is positive, and hence, if the system is running on a critical, the vibration will increase. The question is further complicated by the fact that the motion of the shoe is also vibratory and hence a simple analogy like the excitation of a violin string by its bow does not hold.

When excessive vibratory torques exist in a system employing a centrifugal friction coupling they may be accompanied by a falling in the value of the coupling slip (Fig. 24) (readings taken from an installation not classed by the Society). Fortunately, slip can be readily checked by stroboscopic light and a stop watch. One shoe and a point on the driven drum should be marked and the stroboscope triggered from the engine. If the slip is less than 1 per cent the action of the coupling should be carefully examined.



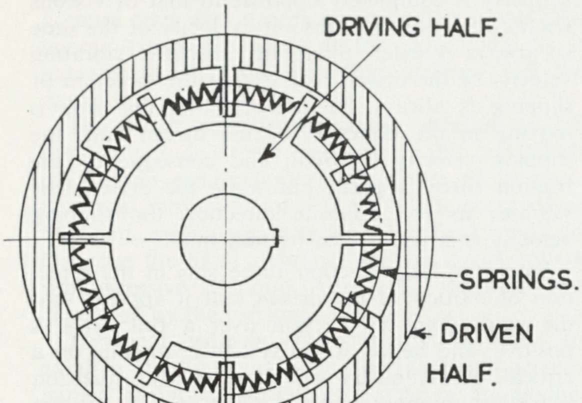

VARIATION OF VIBRATORY TORQUE WITH COUPLING SLIP.

FIG 24

(iii) Spring Coupling

This device (Fig. 25) is a method by which additional flexibility may be introduced into a transmission system. It generates very little damping but can be made to detune by fitting a second helical spring inside each one illustrated, this second spring has initial end clearance and hence does not come into action until the vibratory torque reaches a predetermined value, the stiffness of the coupling then changes and detuning occurs.

Slackness in the springs illustrated reduces the effective stiffness of the coupling and might permit undesirable criticals to enter the running range, Trace K. It is unlikely that this change in stiffness would be apparent in a static test on the coupling.




PRINCIPLE OF ONE TYPE OF SPRING COUPLING.

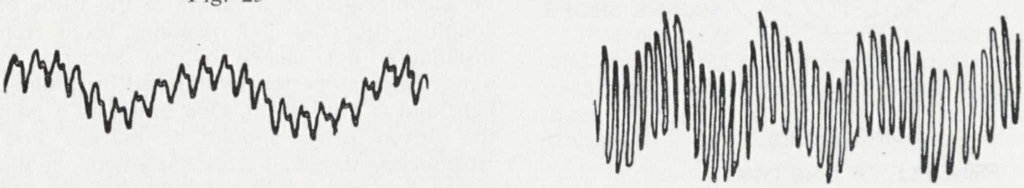
Fig. 25

Removing the springs and checking them in the laboratory (Fig. 26) might reveal some defect but unless the springs were replaced with a small amount, 0·5 mm., initial compression, the dynamic stiffness of the coupling would probably differ from the designed value. It is known that slackness at other points in a transmission system, e.g., a loose propeller or excessive backlash in gears, can reduce the speed at which a critical occurs and also broaden its range.

### Engine and Propeller Excited Machinery and Hull Vibration

It is convenient to distinguish between two distinct types of hull vibration: —

(*a*) General Hull Vibration. Here the hull vibrates as a beam in either a vertical or horizontal mode, or a combination of both (Fig. 27). The torsional mode has not been included as it is comparatively rare.



Trace K

Correct Springs — Slack Springs

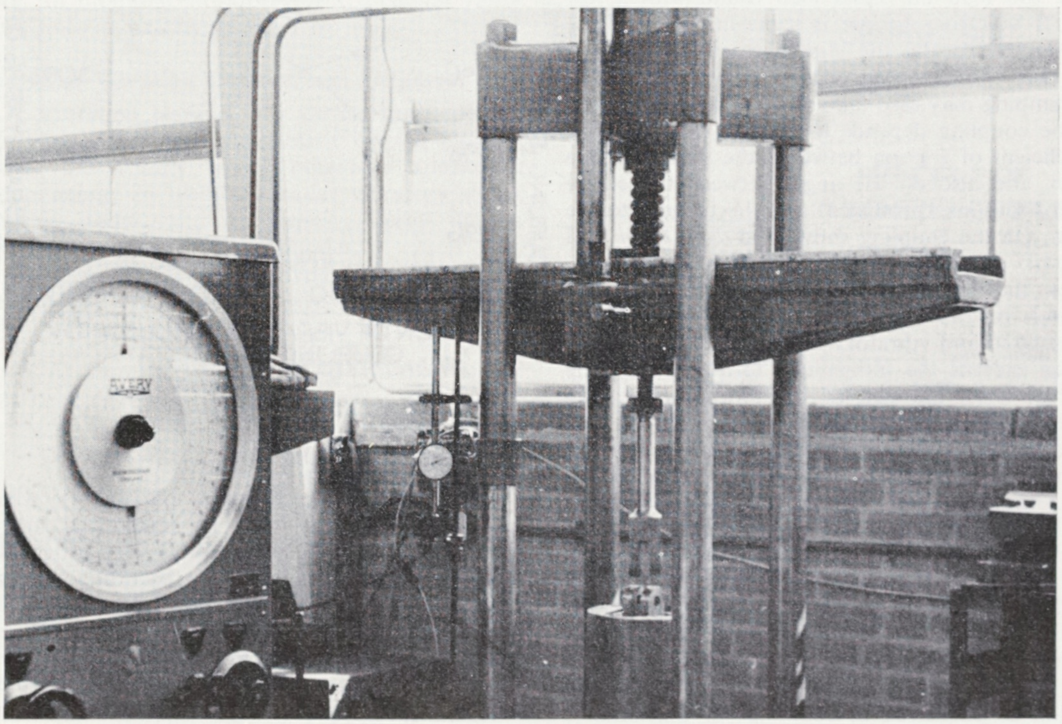
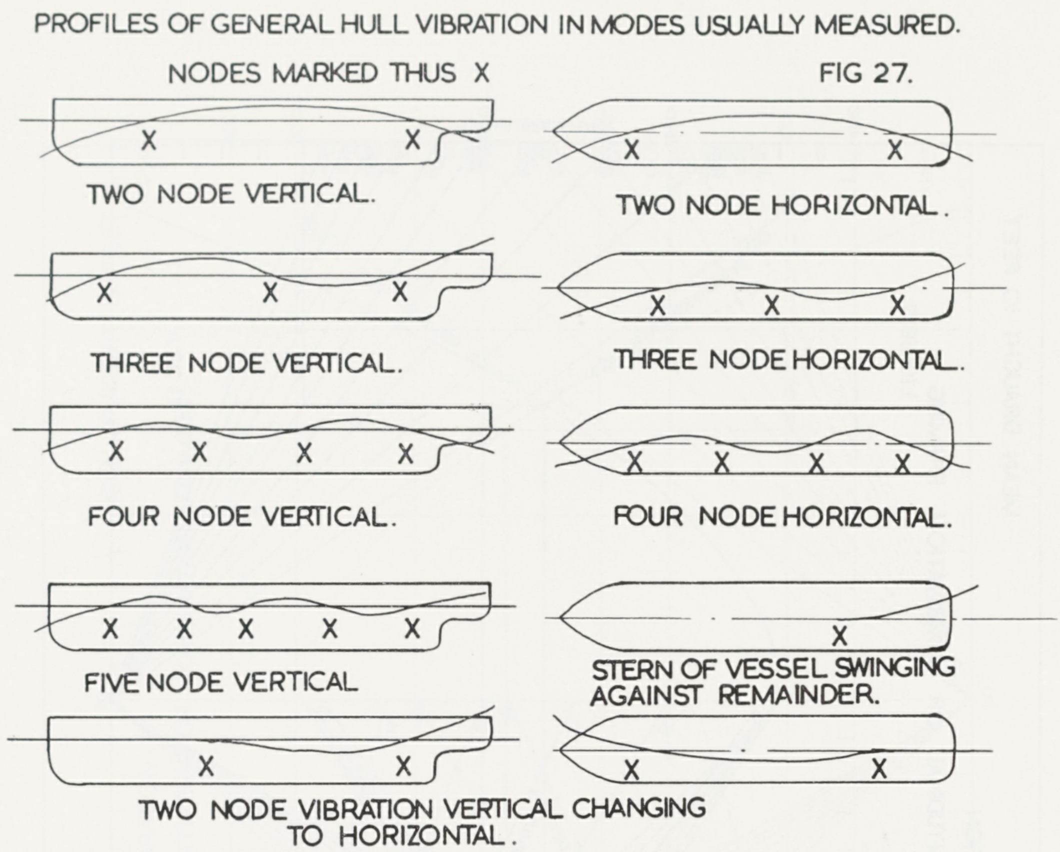


Fig. 26

Calibrating coupling spring

The tensile testing machine in the Society's Research Laboratory, Crawley, Sussex




(*b*) Local Hull Vibration. Here part of the ship's structure or an isolated fitting vibrates owing to the natural frequency of its mass-elastic system coinciding with the frequency of some exciting force.

**General Hull Vibration**

When investigating general hull vibration on board ship it is useful to have a quick method of estimating the probable mode of vibration encountered; for this purpose Figs. 28a to 28f and Fig. 29 have been drawn for tankers. These charts have been based on the formula given in Ref. 4, and Figs. 28a to 28f have been drawn for mean draughts from 10 ft. to 35 ft. in 5 ft. increments.

The value of the natural frequency in the two-node vertical mode for a tanker at, say, 25 ft. mean draught, is estimated from Fig. 28d as follows:—

Estimate the equivalent depth as shown in Fig. 30 (for a tanker this will be equal to the moulded depth) and from the appropriate point on the x axis of Fig. 28d project a line vertically to cut the appropriate load draught line, thence horizontally to the block coefficient line, vertically to the breadth (moulded), horizontally to the curved line on the right hand side of the chart, vertically to the length between perpendiculars and horizontally to the frequency axis.

This frequency will probably be within about 10 per cent of the two-node vertical. Having estimated the two-node vertical frequency, the frequencies for other common modes can be estimated from Fig. 29. Charts for cargo ships, where Fig. 30 is necessary, are being prepared and will be included in the printed "Discussion".

There are two methods usually employed to reduce this type of vibration, the first being to alter the distribution of the masses along the ship in order to remove the natural frequency from the forcing frequency. Experience and theory indicate that:—

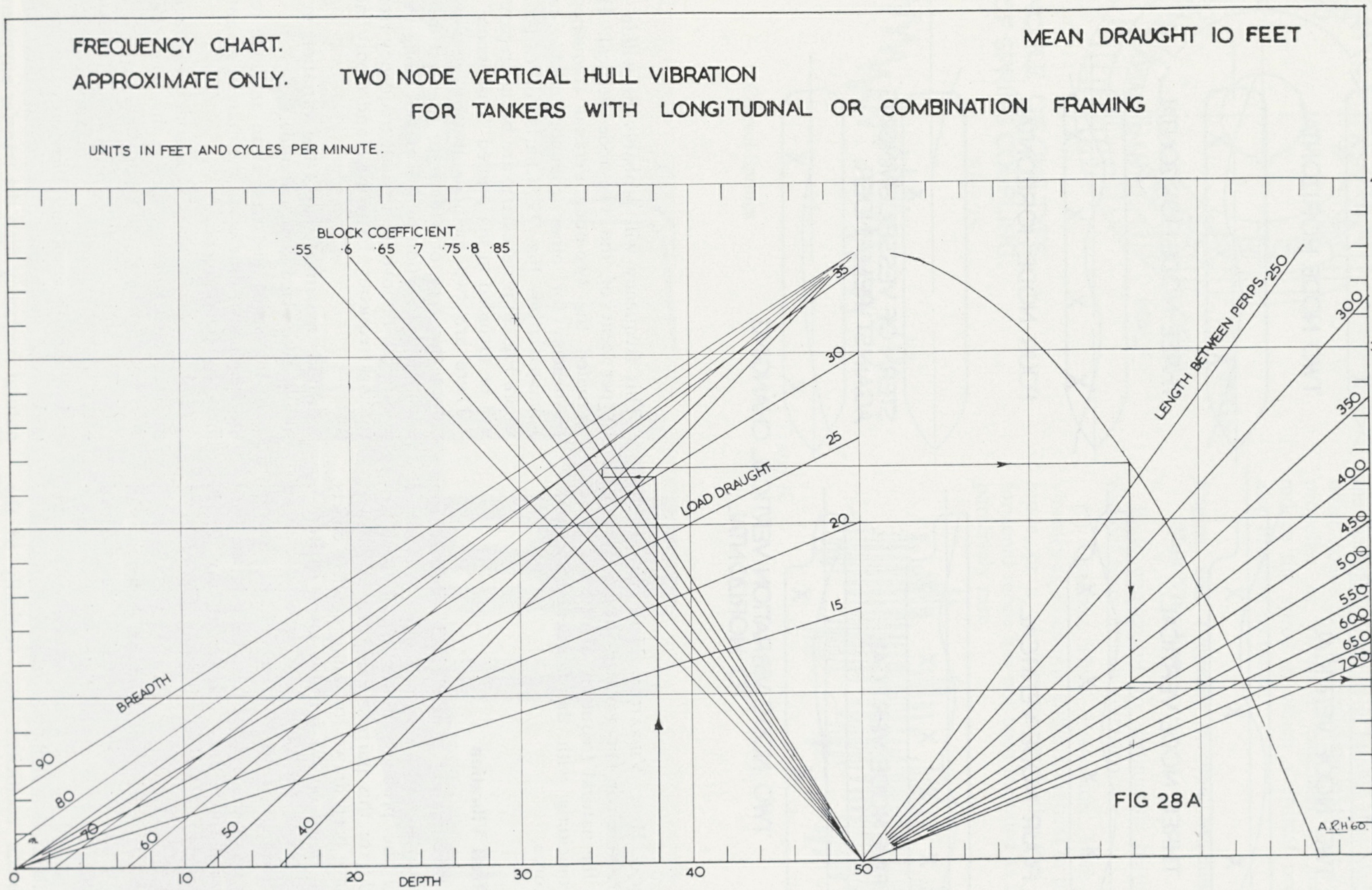
(*a*) For maximum effect the variation in mass should take place at an antinode.

(*b*) Increasing the mass at an antinode reduces the frequency; decreasing the mass at an antinode increases the frequency.

(*c*) Variation in mass at a node has practically no effect on frequency since at this point the mass does not partake in the vibration.

(*d*) The antinodes at the fore and aft ends of the vessel are usually those of maximum amplitude, and filling or emptying the fore and aft peak tanks will probably have more effect on the natural frequency than the transfer anywhere else of comparable masses.

(*e*) Vibration may appear (or disappear) on a vessel and yet the change in draught or trim be negligible.


FREQUENCY CHART.
APPROXIMATE ONLY.
TWO NODE VERTICAL HULL VIBRATION
FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING
MEAN DRAUGHT 10 FEET
UNITS IN FEET AND CYCLES PER MINUTE.
BLOCK COEFFICIENT
·55 ·6 ·65 ·7 ·75 ·8 ·85
LOAD DRAUGHT
35
30
25
20
15
BREADTH
90
80
70
60
50
40
DEPTH
0
10
20
30
40
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LENGTH BETWEEN PERPS. 250
300
350
400
450
500
550
600
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FREQUENCY.
100
200
300
400
A.R.H.'60.
FIG 28A

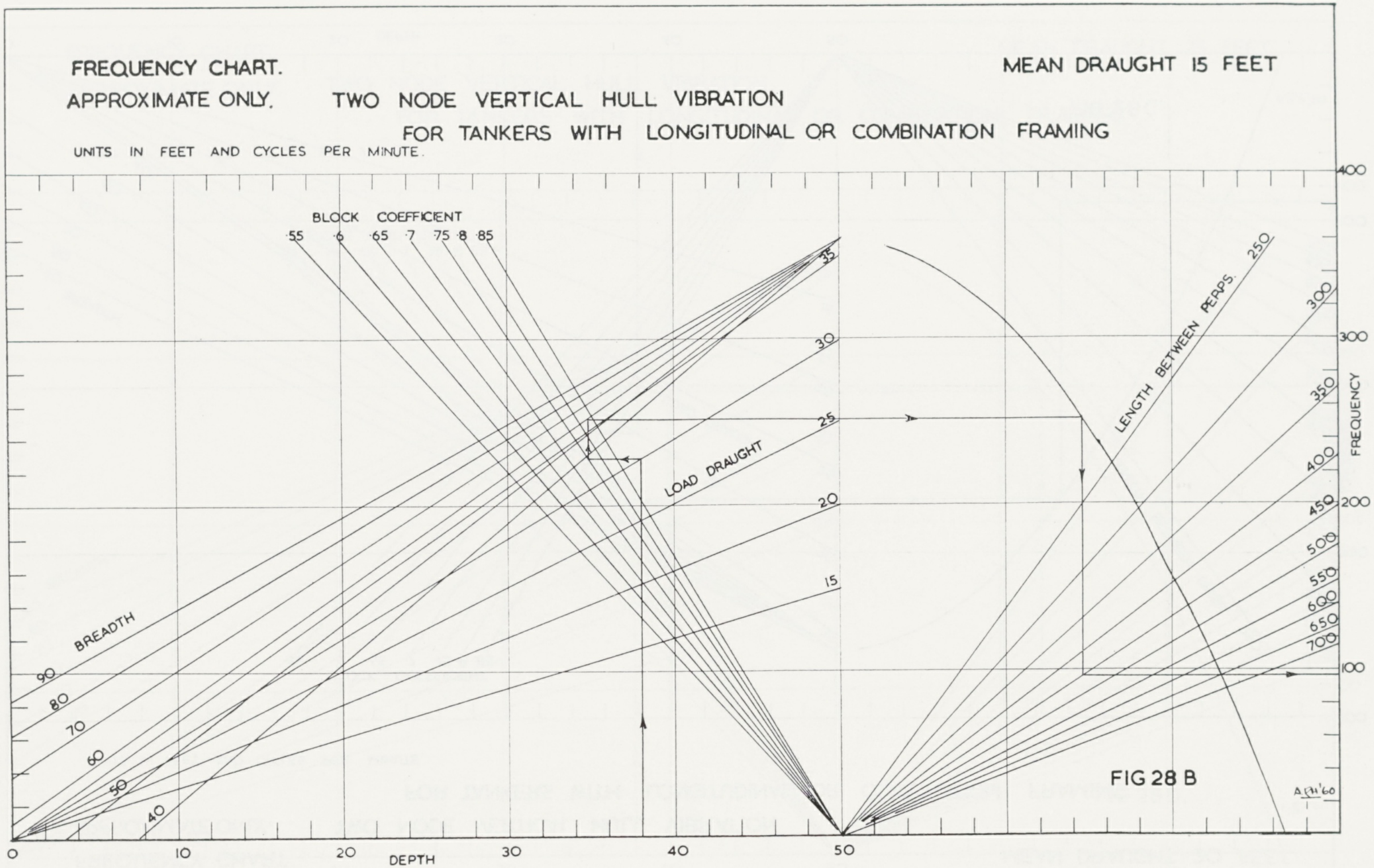

FREQUENCY CHART.
APPROXIMATE ONLY.
TWO NODE VERTICAL HULL VIBRATION
FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING
MEAN DRAUGHT 15 FEET
UNITS IN FEET AND CYCLES PER MINUTE.
BLOCK COEFFICIENT
·55 ·6 ·65 ·7 ·75 ·8 ·85
BREADTH
90
80
70
60
50
40
LOAD DRAUGHT
35
30
25
20
15
LENGTH BETWEEN PERPS.
250
300
350
400
450
500
550
600
650
700
FREQUENCY
400
300
200
100
DEPTH
0
10
20
30
40
50

FIG 28 B

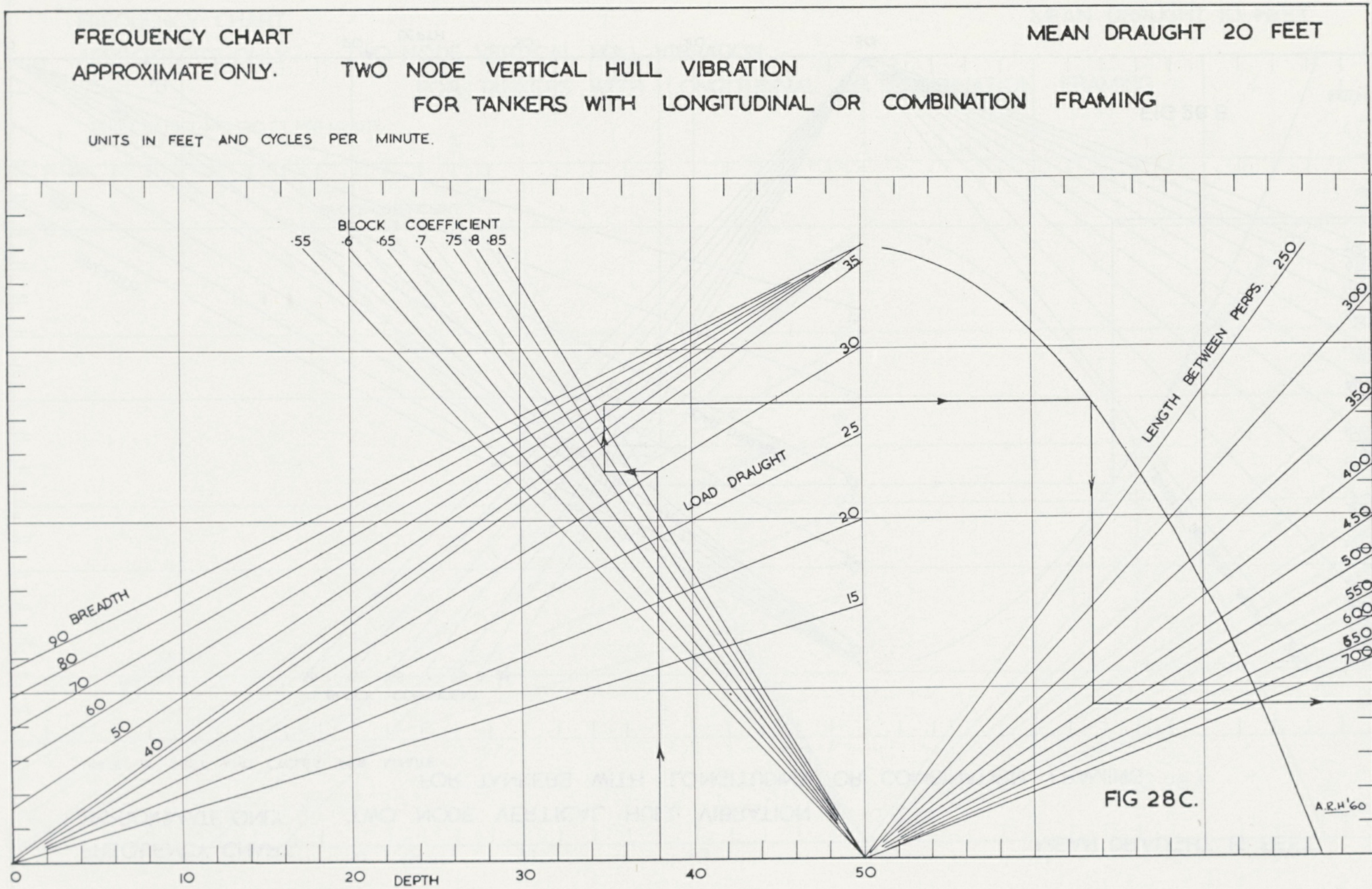

FREQUENCY CHART
APPROXIMATE ONLY.
TWO NODE VERTICAL HULL VIBRATION
FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING
MEAN DRAUGHT 20 FEET
UNITS IN FEET AND CYCLES PER MINUTE.
BLOCK COEFFICIENT
·55 ·6 ·65 ·7 ·75 ·8 ·85
LOAD DRAUGHT
35
30
25
20
15
BREADTH
90
80
70
60
50
40
LENGTH BETWEEN PERPS.
250
300
350
400
450
500
550
600
650
700
FREQUENCY.
400
300
200
100
DEPTH
0
10
20
30
40
50
A.R.H.'60

FIG 28C.

FREQUENCY CHART.

APPROXIMATE ONLY. TWO NODE VERTICAL HULL VIBRATION

FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING

MEAN DRAUGHT 25 FEET

UNITS IN FEET AND CYCLES PER MINUTE.

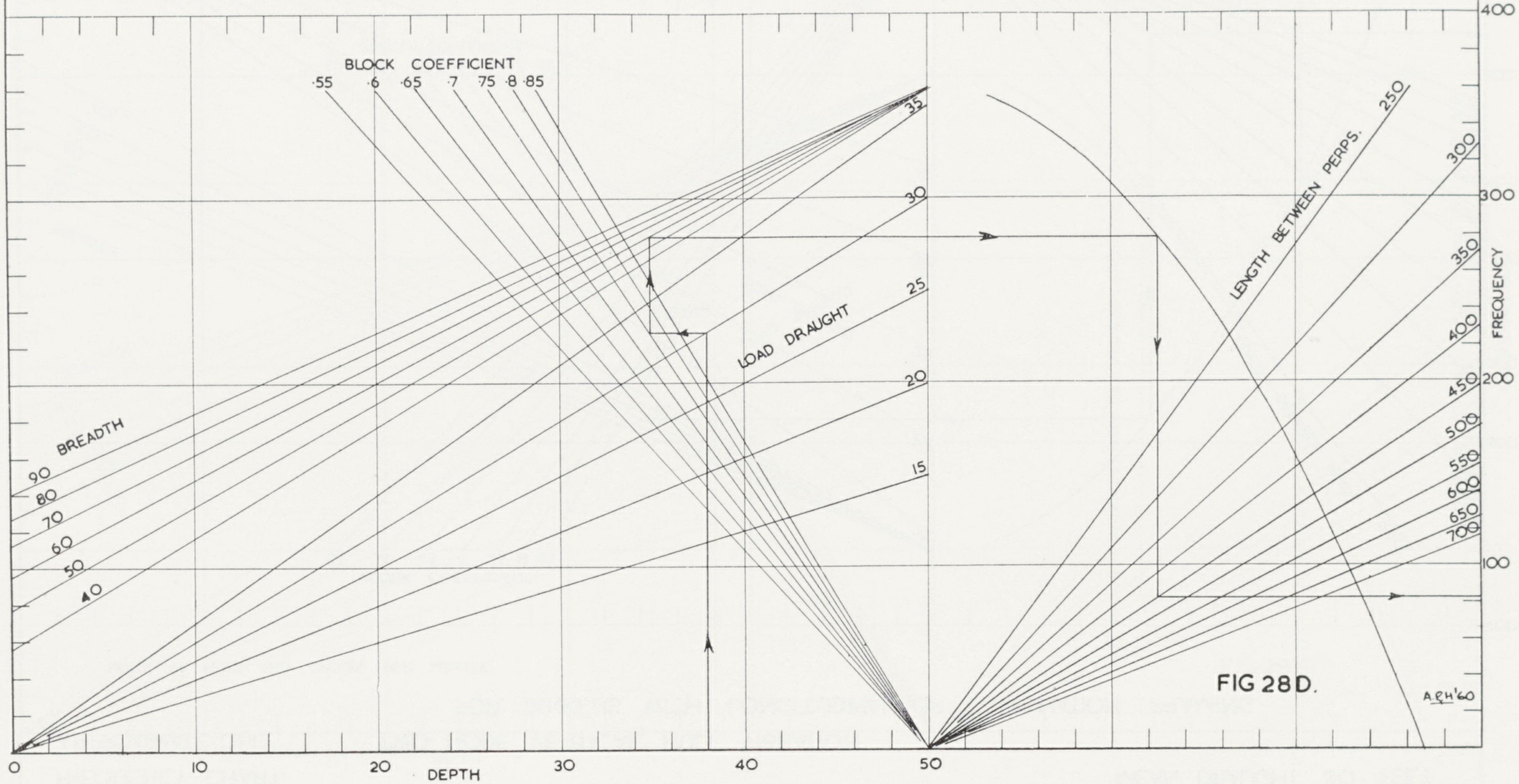



FIG 28 D.

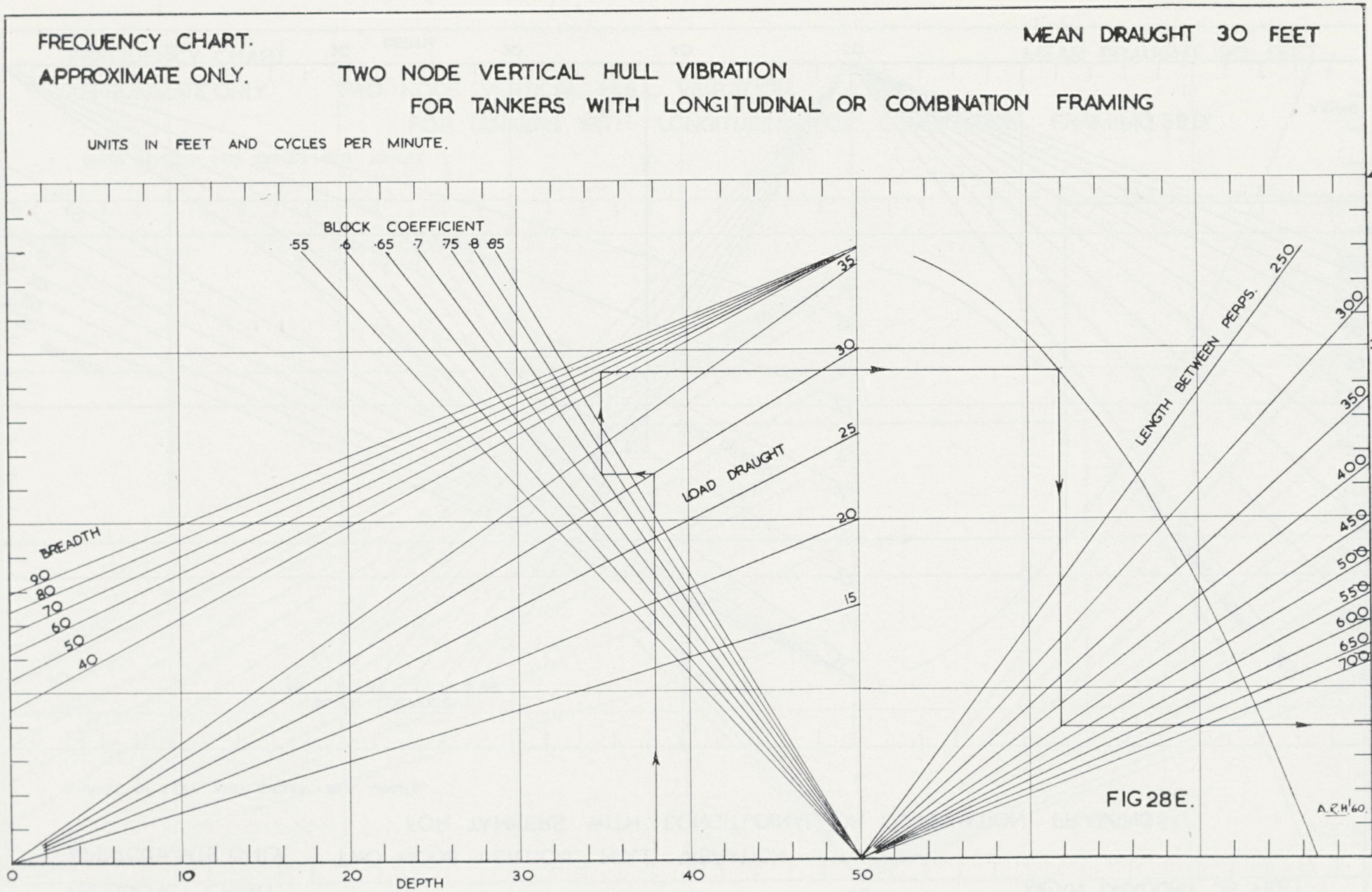
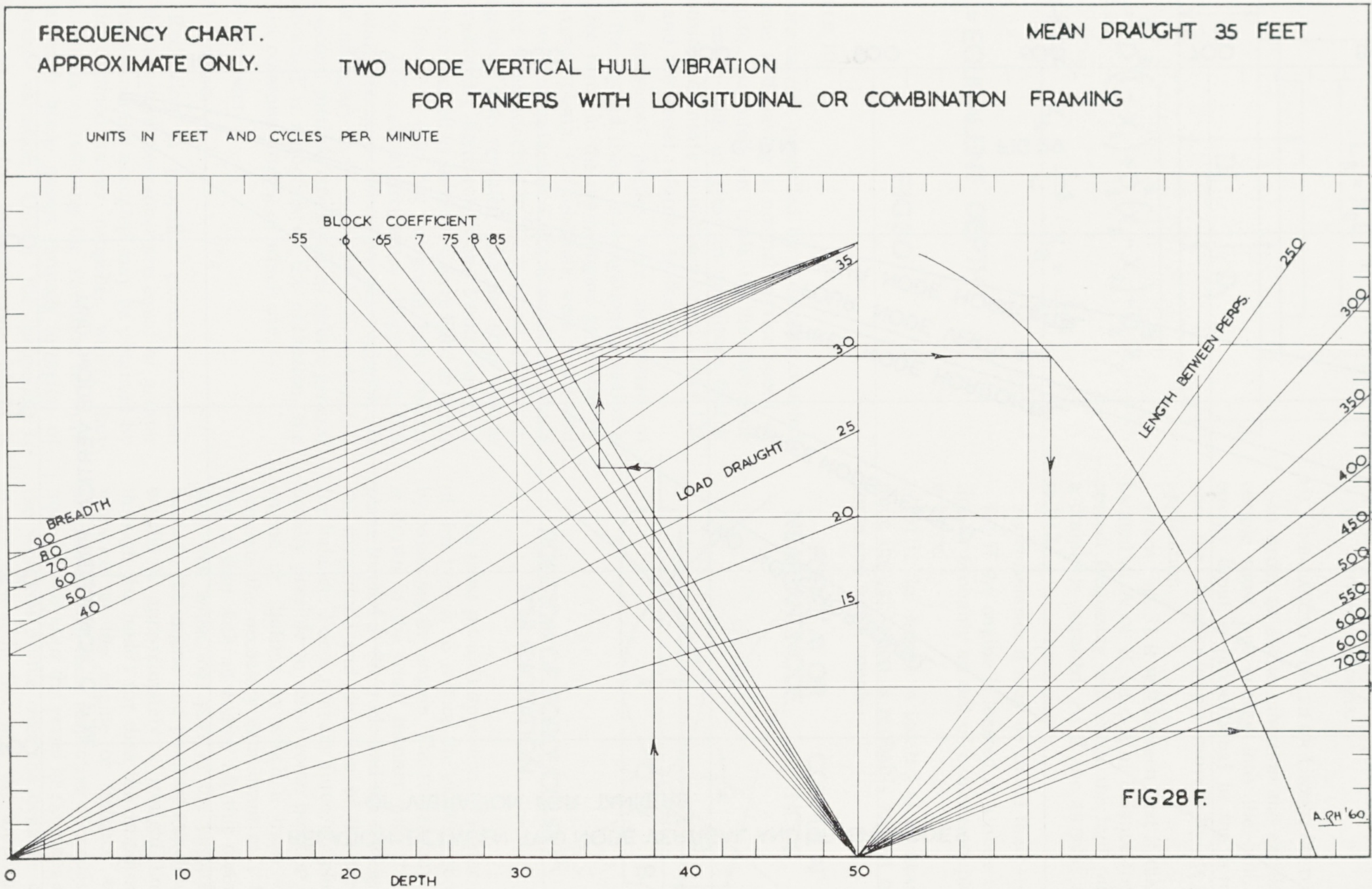

FREQUENCY CHART.
APPROXIMATE ONLY.
TWO NODE VERTICAL HULL VIBRATION
FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING
MEAN DRAUGHT 30 FEET
UNITS IN FEET AND CYCLES PER MINUTE.
BLOCK COEFFICIENT
·55 ·6 ·65 ·7 ·75 ·8 ·85
BREADTH
90 80 70 60 50 40
LOAD DRAUGHT
35 30 25 20 15
LENGTH BETWEEN PERPS.
250 300 350 400 450 500 550 600 650 700
FREQUENCY
400 300 200 100
DEPTH
0 10 20 30 40 50
A.R.H.'60.

FIG 28E.


FREQUENCY CHART.
APPROXIMATE ONLY.
MEAN DRAUGHT 35 FEET
TWO NODE VERTICAL HULL VIBRATION
FOR TANKERS WITH LONGITUDINAL OR COMBINATION FRAMING
UNITS IN FEET AND CYCLES PER MINUTE
BLOCK COEFFICIENT
·55 ·6 ·65 ·7 ·75 ·8 ·85
BREADTH
90
80
70
60
50
40
LOAD DRAUGHT
35
30
25
20
15
LENGTH BETWEEN PERPS.
250
300
350
400
450
500
550
600
600
700
FREQUENCY
400
300
200
100
0
10
20
30
40
50
DEPTH
FIG 28 F.
A.RH '60.

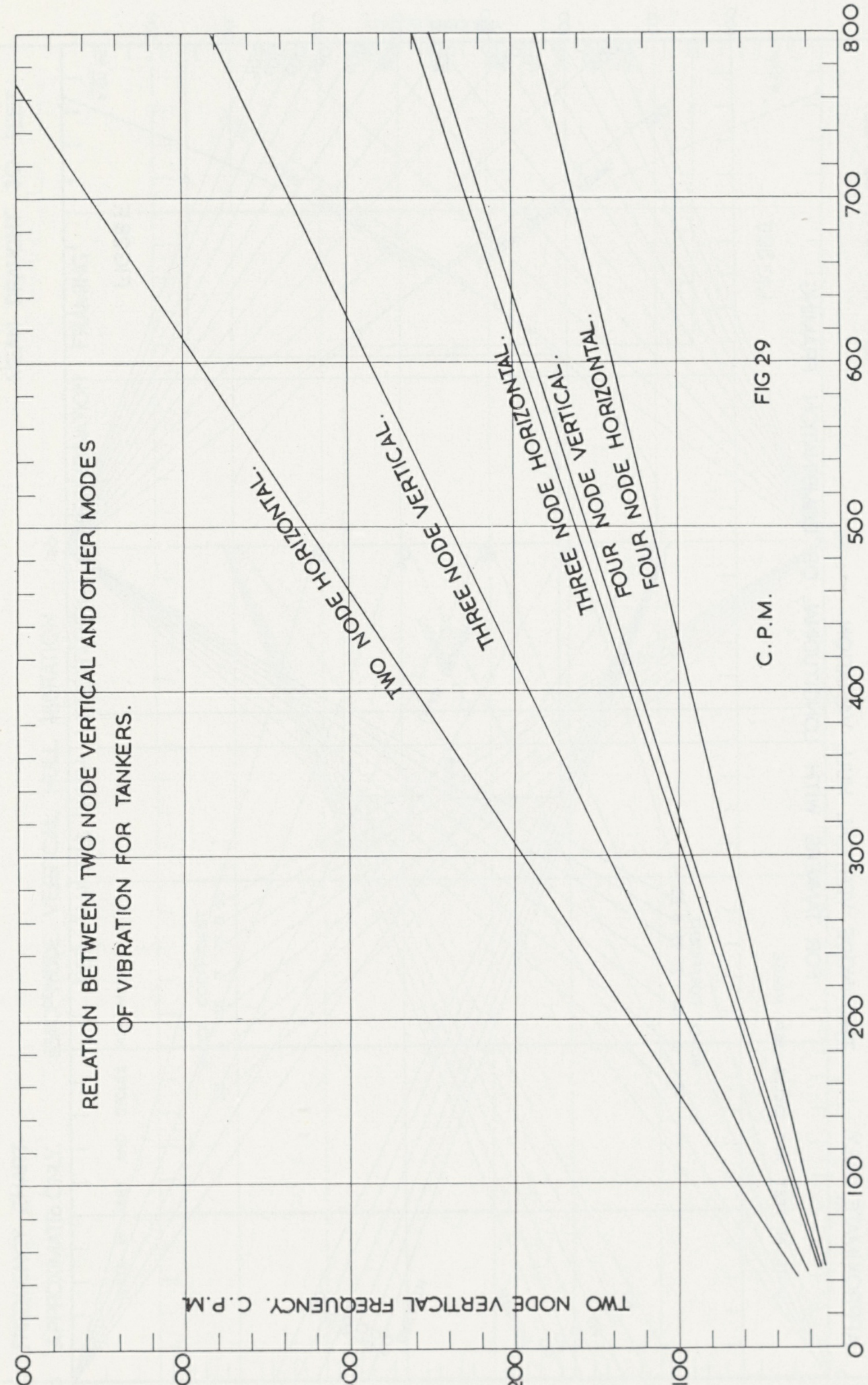
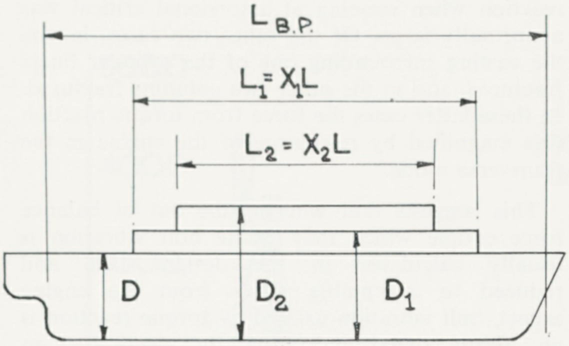

RELATION BETWEEN TWO NODE VERTICAL AND OTHER MODES
OF VIBRATION FOR TANKERS.
TWO NODE HORIZONTAL.
TWO NODE VERTICAL.
THREE NODE HORIZONTAL.
THREE NODE VERTICAL.
FOUR NODE HORIZONTAL.
FOUR NODE HORIZONTAL.
TWO NODE VERTICAL FREQUENCY. C.P.M.
C.P.M.
0
100
200
300
400
500
600
700
800
100
200
300
400
500

FIG 29




$$D_E = \sqrt[3]{D^3(1 - X_1) + D_1^3(X_1 - X_2) + D_2^3 X_2}$$

WHERE $X_1 = \frac{L_1}{L}$ ; $X_2 = \frac{L_2}{L}$

$D_E$ = EQUIVALENT DEPTH.

FIG30.

Example 10

An ore carrier, propelled by a directly coupled oil engine and having a normal service speed of 130 r.p.m., vibrated on trials in the two-node vertical mode with so great an amplitude that it was considered unsafe to increase speed above 123 r.p.m. and the vessel returned to the yard.

While interested parties were summoned to witness the second trials, investigations revealed a small free force in the main engine generated by the scavenge pump. Calculations were made and weights were manufactured which would eliminate this force when attached to the flywheel. However, investigations also revealed that the ship was in an exceptionally light condition. Tanks, some of which were located at antinodes, were filled in order to put the ship into her sea-going light ballast condition. The natural frequency dropped to 116 r.p.m. and subsequent vibration was negligible. It was not necessary to fit the extra balance weights.

The second method employed to reduce general hull vibration is reduction of the excitation, the two most common origins of which are:—

(*a*) Propeller.

(*b*) Engine.

(*a*) Reduction in propeller excited vibration when the aperture clearances are equal or greater than those generally accepted may be obtained by methods outlined under propeller whirl; they consist mainly in reducing the variation in work done as each blade passes through a region of high wake variation. Unless the propeller is damaged so that, for instance, one blade is incorrectly pitched or out of balance, it is unusual for the propeller to excite excessive vibration at the same frequency as the propeller shaft revolutions per minute.

(*b*) Engine excited hull vibration is practically confined to vessels fitted with reciprocating engines, and in such engines the exciting forces arise from:—

(i) Unbalanced forces or unbalanced couples.

(ii) Torque reactions.

(i) Unbalanced Forces or Unbalanced Couples.

In order to excite vibration the exciting force/couple must put energy into the hull, and the energy input is proportional to the force/couple and the distance/angle moved by its point of application.

From Fig. 31 it will be seen that if the engine is located at A or B, an out of balance force of the correct frequency will excite the hull, while at C, a couple is required. At C the angular amplitude is $\theta/2$.

As corollaries it may be stated that:—

(*a*) If the engine is located at a node the excitation is probably an out of balance couple and not a force.

(*b*) If the engine is located at or near an antinode the excitation is probably an out of balance force and not a couple.

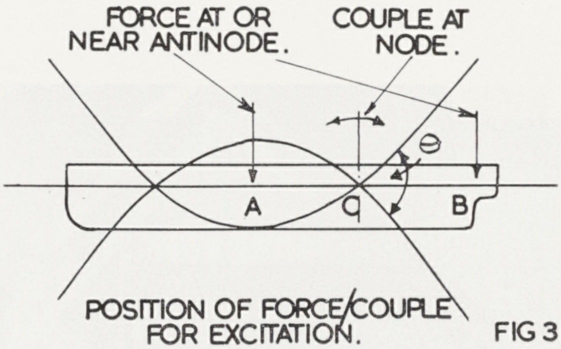



FIG 31

The most positive approach to engine excitation of this type is to reduce the exciting force/couple by balancing the engine. The force/couple polygon is drawn in the usual manner with the reference plane located at the node and the closing line gives the magnitude and direction of the force/couple for balance. For a primary force/couple it is then usually possible to select some point in either the engine or shafting at which a mass which will generate the necessary equilibrant may be placed. For a ship with an engine aft this method works very well when that part of the vibration profile between the engine and point of attachment of the weight is approximately a straight line passing through the node; for then the amplitudes of the vibration at the engine or balance weight are proportional to their respective distances from the node. However, if the vessel has engines amidships, the vibration profile over the distance considered is not a straight line and the amplitude is not proportional to the distance from the node; a correction must be made for this effect when designing the balance weight. The reason for this is that the purpose of the balance weight is not

so much to balance a force as to counteract an energy input into the mass-elastic system of the ship, and energy input is proportional to exciting force multiplied by amplitude. Counteraction of secondary engine out-of-balance can be taken by driving from the engine a shaft to which is attached a suitable weight. The weight must, of course, revolve at twice the speed of the engine.

(ii) Torque Reactions

Fortunately, this type of engine excited general hull vibration is rare, but in the three cases recalled most easily by the writer, the engines were damaged. On the vessel (not classed with the Society) from which the crankshaft shown in Fig. 32 was removed, hull vibration was sufficient to cause ripples in the water alongside the vessel. It is interesting to compare the appearance of the crankshaft fracture with those of two specimens broken in the laboratory by torsional fatigue (Figs. 34 and 35). Fitting a new damper eliminated both engine torsional and hull horizontal vibration (Fig. 33). It appears that the variation in torque reaction when running at a torsional critical was abnormally large. Of the other two cases, in one the casting surrounding one of the cylinder liners fractured, and in the other two columns fractured. In these latter cases the force from torque reaction was magnified by resonance of the engine in the transverse mode.

This suggests that whereas the out of balance force/couple which may excite hull vibration is usually calculated in the design stage and reduced to acceptable limits from the engine aspect, hull vibration excited by torque reaction is an alarm signal indicating the need for an investigation into the transverse and torsional characteristics of the engine.

One method by which it is sometimes possible to distinguish between force/couple excitation and torque reaction excitation is by comparing frequencies. Force/couple excitation usually occurs at once or twice engine revolutions per minute; torque reaction excitation usually occurs at engine firing frequency.

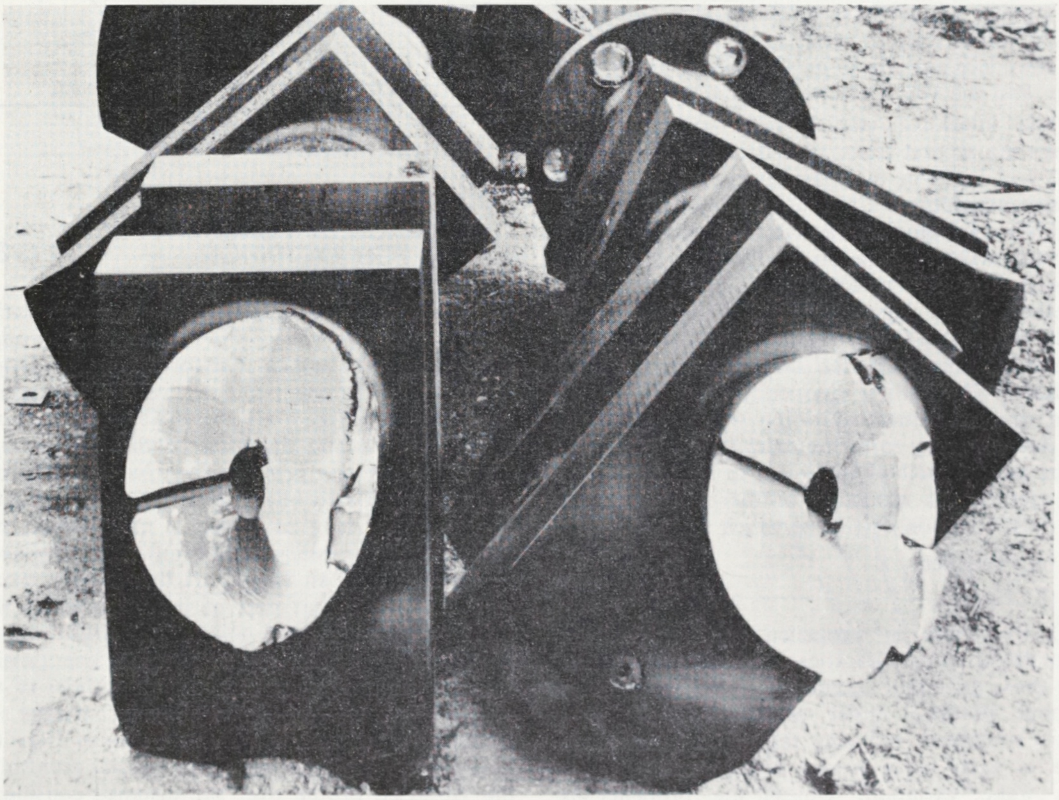
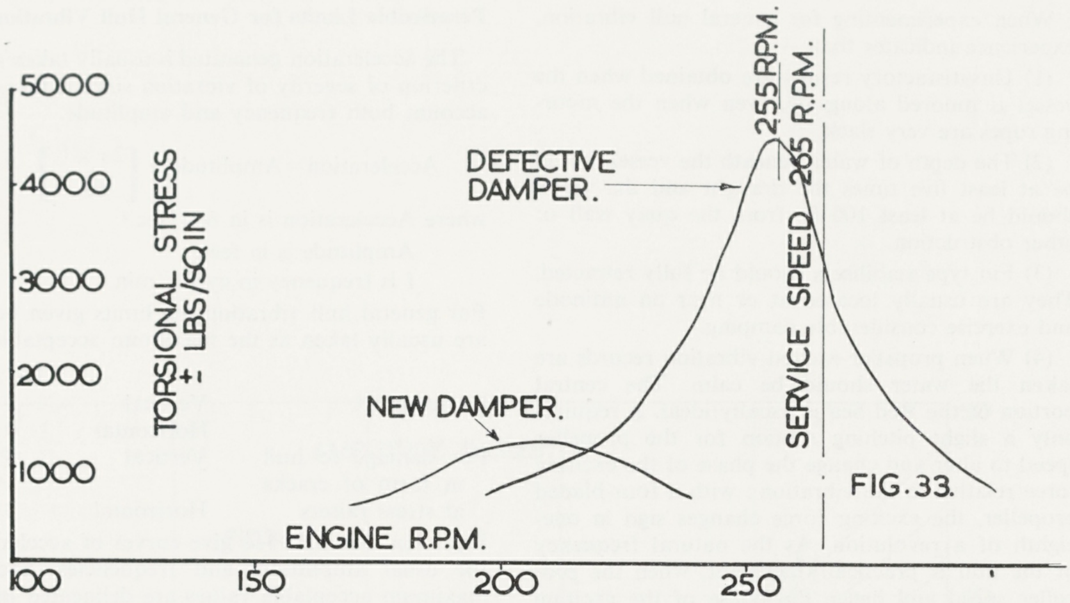


Fig. 32

Torque reaction generated by the torsional vibration which fractured this crankshaft was sufficiently large to vibrate the hull and cause ripples in the water alongside the vessel




A defective damper permitted the torsional stress to rise to a dangerous level

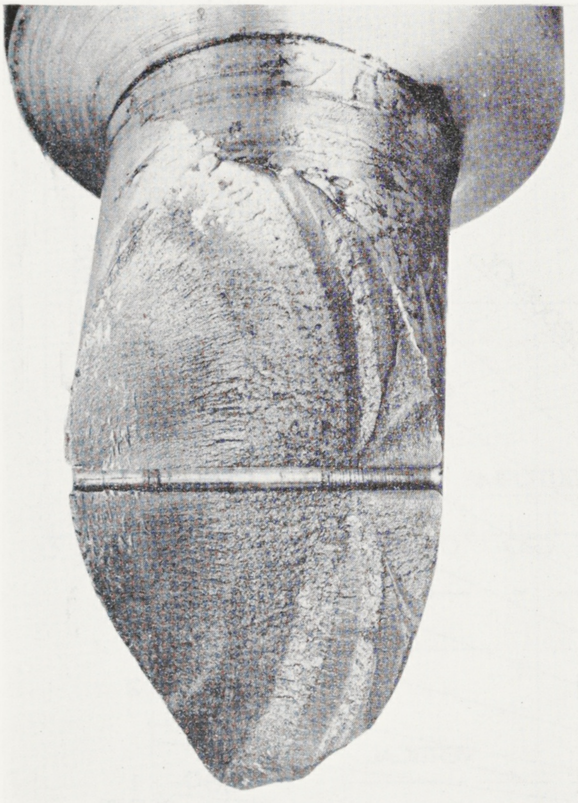


Fig. 34

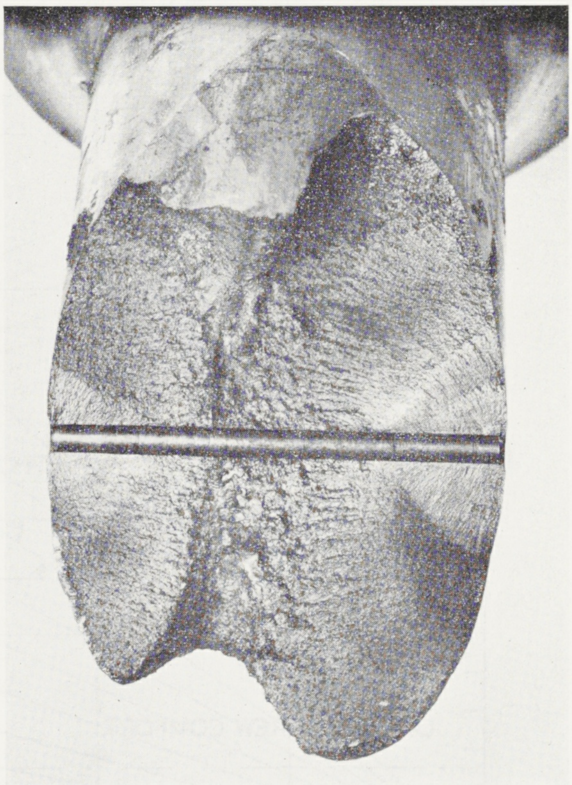


Fig. 35

Specimens broken by torsional fatigue in the Society's Research Laboratory

When experimenting for general hull vibration, experience indicates that: —

(1) Unsatisfactory results are obtained when the vessel is moored alongside, even when the mooring ropes are very slack.

(2) The depth of water beneath the vessel should be at least five times the draught and the vessel should be at least 100 ft. from the quay wall or other obstruction.

(3) Fin type stabilisers should be fully retracted. They are usually located at or near an antinode and exercise considerable damping.

(4) When propeller-excited vibration records are taken the water should be calm. The central portion of the Red Sea is usually ideal. It requires only a slight pitching motion for the propeller speed to alter and change the phase of the exciting force relative to the vibration; with a four-bladed propeller, the exciting force changes sign in one-eighth of a revolution. As the natural frequency of the hull is practically constant, when the propeller speed and hence the phase of the exciting force changes, the amplitude of the vibration rises and falls, and may give the erroneous impression that two exciting forces are present and are beating together.

**Permissible Limits for General Hull Vibration**

The acceleration generated is usually taken as the criterion of severity of vibration since it takes into account both frequency and amplitude.

$$\text{Acceleration} = \text{Amplitude} \times \left[\frac{2\pi \times f}{60}\right]^2$$

where Acceleration is in feet/sec.$^2$

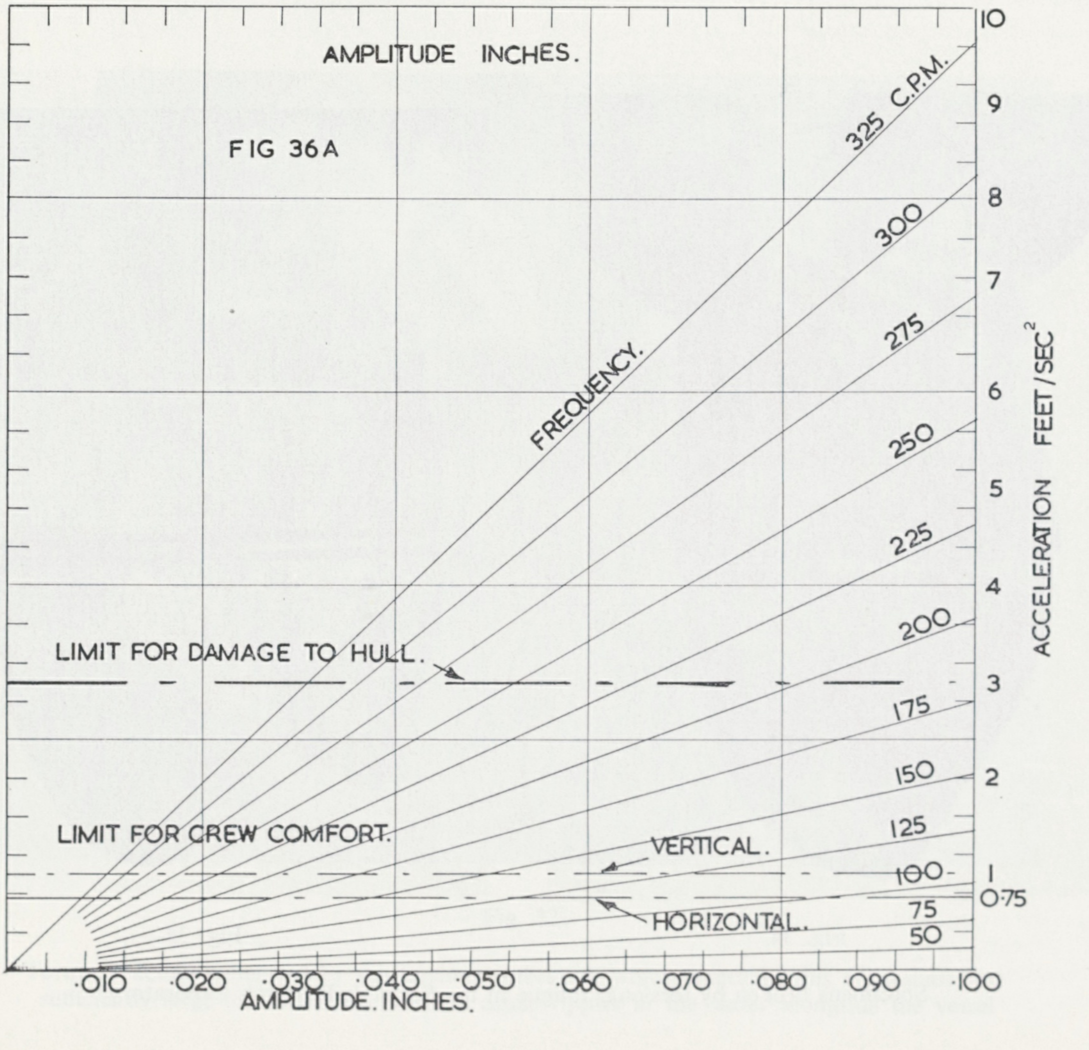
Amplitude is in feet.

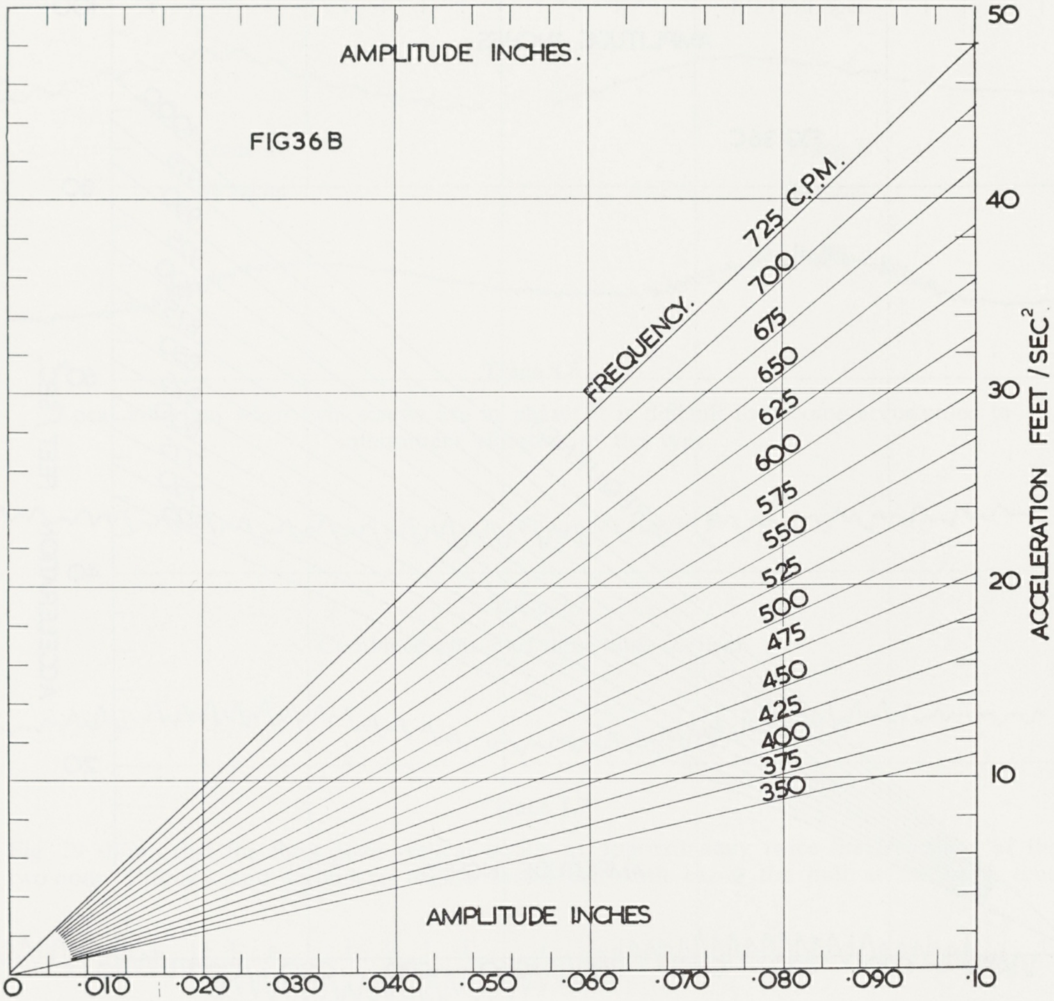
f is frequency in cycles/min.

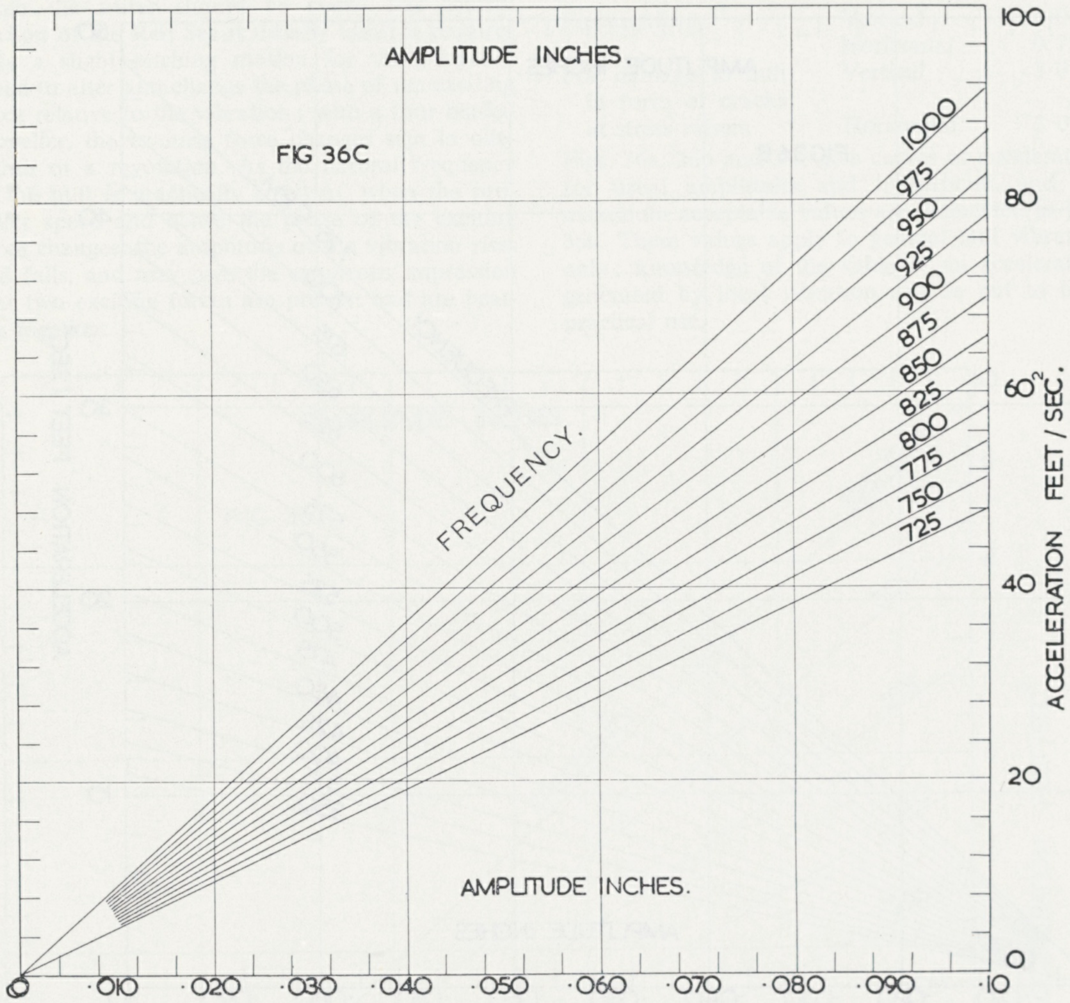
For general hull vibration the limits given below are usually taken as the maximum acceptable: —

| | | feet/sec.$^2$ |
|---|---|---|
| For comfort | Vertical | 1·0 |
| | Horizontal | 0·75 |
| For damage to hull in form of cracks at stress raisers | Vertical | 3·0 |
| | Horizontal | 3·0 |

Figs. 36a, 36b and 36c give curves of acceleration for usual amplitudes and frequencies, and the maximum acceptable values are delineated in Fig. 36a. These values apply to general hull vibration only; knowledge of the value of an acceleration generated by local vibration can be put to little practical use.




AMPLITUDE INCHES.
FIG36B
FREQUENCY.
725 C.P.M.
700
675
650
625
600
575
550
525
500
475
450
425
400
375
350
AMPLITUDE INCHES
50
40
30
20
10
ACCELERATION FEET / SEC²
0
·010
·020
·030
·040
·050
·060
·070
·080
·090
·10

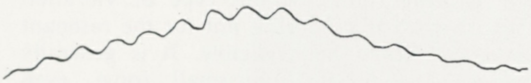

AMPLITUDE INCHES.
FIG 36C
FREQUENCY.
1000
975
950
925
900
875
850
825
800
775
750
725
100
80
60
40
20
0
ACCELERATION FEET / SEC.$^2$
AMPLITUDE INCHES.
0
·010
·020
·030
·040
·050
·060
·070
·080
·090
·10

Traces L1 to L13 are records taken with a Geiger vibrograph of various types of hull vibration. Trace L14 was on a tanker in a moderate sea, and although the vessel was steaming at a hull critical speed, the slight rolling and pitching prevented measurements of any value.

Tanker. Horizontal Two-Node

Trace L1

Resonance. 99 r.p.m.



Trace L2

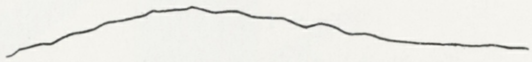
98 r.p.m.

Trace L3

97 r.p.m.

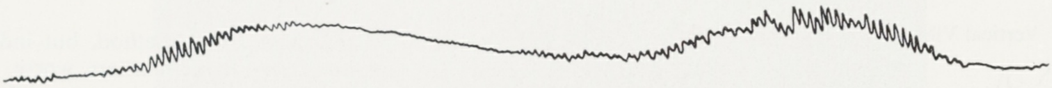
Trace L4

96 r.p.m.



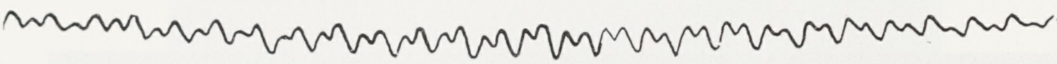
Trace L5

95 r.p.m.



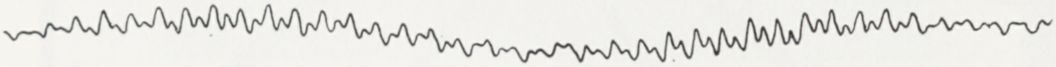
Trace L6

Local vibration when twin screws are in phase. It is difficult to become accustomed to intermittent vibration of this type



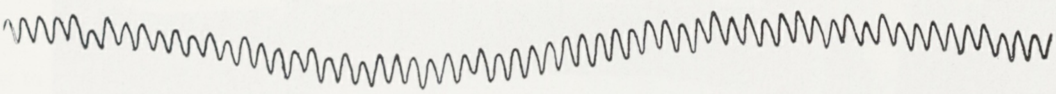
Trace L7

Combined two- and three-node vertical



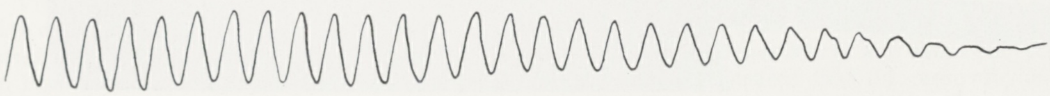
Trace L7

Fig. 29 shows that the three-node vertical occurs at approximately twice the frequency of the two-node. Primary and secondary engine forces can both excite the hull at the same time



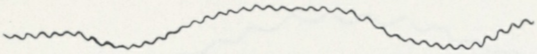
Trace L8

Three-node vertical. Twin screw passenger vessel



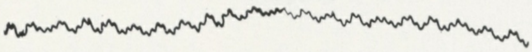
Trace L9

Two-node vertical. Steering flat. Service speed 100 r.p.m. Natural frequency 96 c.p.m. Record taken when 16° helm reduced speed from 100 to approximately 96 r.p.m.



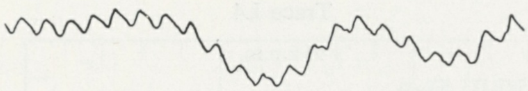
Trace L10

Two-Node Horizontal. Passenger Vessel



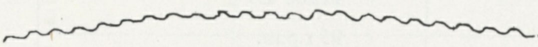
Trace L11

Four-Node Horizontal. Cargo Ship



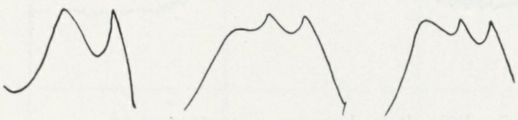
Trace L12

Two-Node Vertical. Cargo Ship



Trace L13

Vertical Vibration. Forepeak. Tanker



Trace L14

Vertical. Tanker in Moderate Sea. Record of no value

It is fairly common for general hull vibration to give rise to local hull vibration—as when a longitudinal bulkhead having a heavy switchbox attached to it is excited by general horizontal vibration of the hull—but much more rare for local hull vibration to give rise to general hull vibration. One example is resonance in the torsional mode of the rudder on its stock when it occurs at the same frequency as one of the horizontal modes of general hull vibration ; the variation of the reaction of the rudder on the pintles applies an exciting force to the hull at an antinode.

**Local Hull Vibration**

The exciting force for this type of vibration can be so small that, were it not for the resonant structure, it would be negligible. It is generally impractical to reduce this small force, even when it is possible to locate and define it, hence the remedy for local hull vibration usually consists of altering the natural frequency of the vibrating system by varying its mass or stiffness or both.

Stiffening is the more usual method, but indiscriminate stiffening may make matters worse. If possible, before the expense of permanent stiffening is incurred, temporary stiffening, such as wooden shores and wire guys, should be fitted to ascertain that stiffening at the proposed position will be effective (Figs. 37 and 37a). This will ensure that the members to which the stiffening

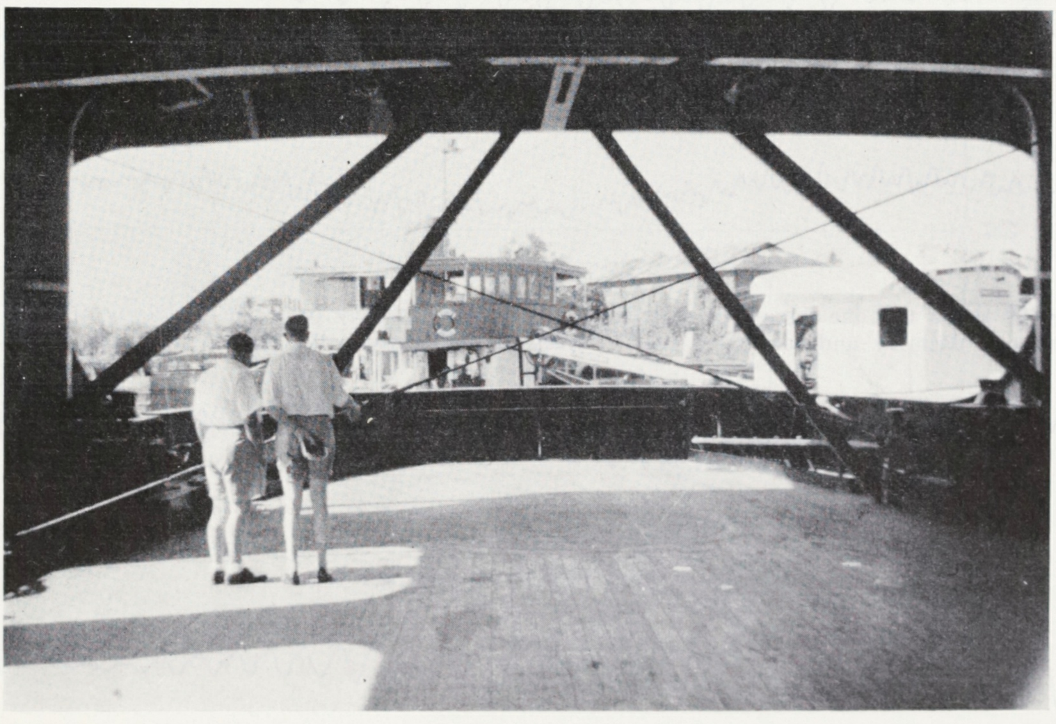


Fig. 37

Teak shores and crosswire bracing fitted beneath bridge at each end of vessel

Fig. 37a

Close-up of teak shores

is to be attached are sufficiently rigid, and that the mass of the stiffening will not nullify its effect.

Local hull vibration reduction is best illustrated by examples.

Example 11

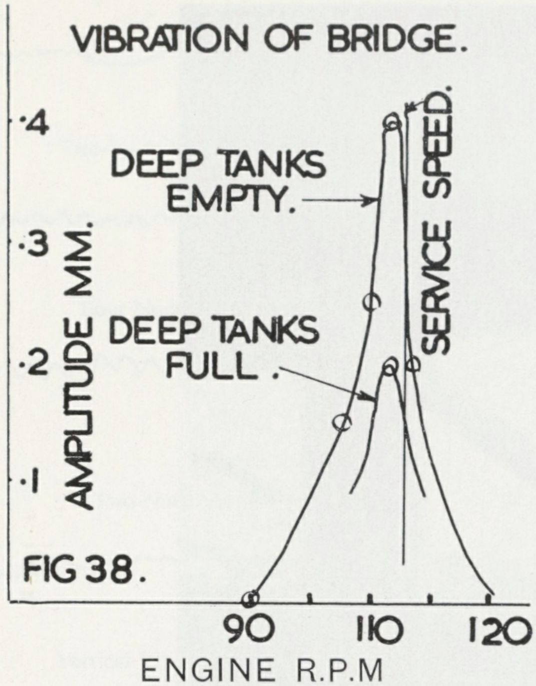
Vibration of a bridge structure situated aft on a dry cargo vessel 485 ft. long. In the light ballast condition the bridge vibrated laterally as indicated in Figs. 38 and 39, causing failure of the electronic aids to navigation and rendering it impossible to use the chart room table, Traces M1 and M2. Filling two large deep tanks immediately forward of the bridge halved the amplitude of the vibration on the bridge and deck below, and eliminated it on the remaining decks.

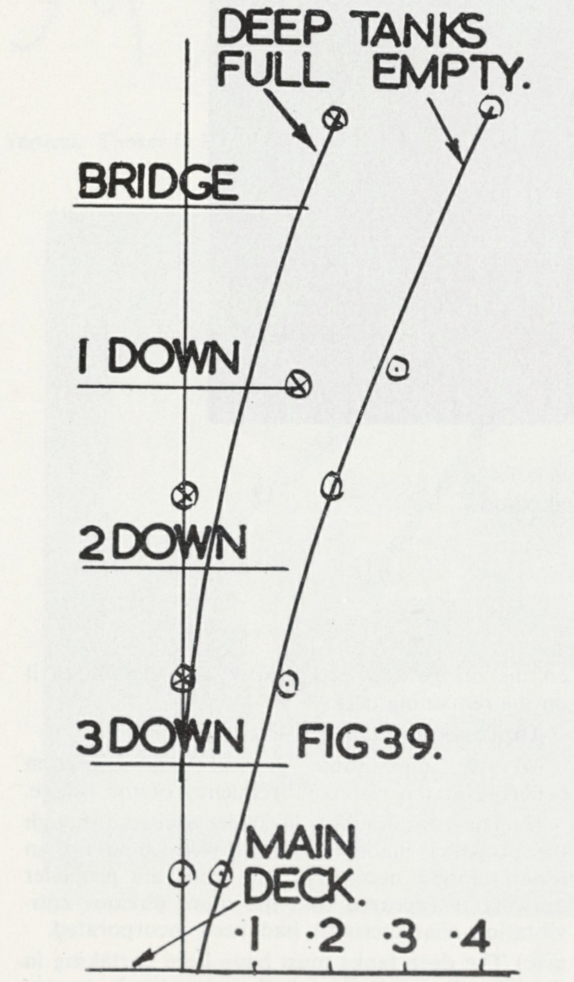
This case is interesting since:—

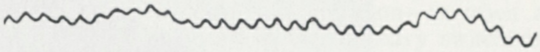
(*a*) No measurable general hull vibration occurred at the resonant frequency of the bridge.

(*b*) The vibration was propeller excited although the propeller blade clearances were greater than usually found necessary, and from the propeller drawing it appeared that the more obvious anti-vibration characteristics had been incorporated.

(*c*) The deep tanks must have been partaking in the vibration even though their amplitude was so small as to be imperceptible.

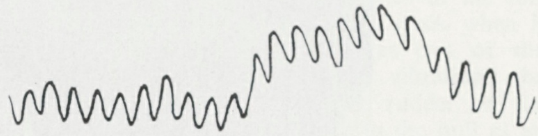


Trace M1

Bridge. Transverse Vibration



Trace M2

Radar Set. Transverse Vibration

Shortly after this trace was taken the radar set ceased to function

EXAMPLE 12

On a certain vessel the steering gear switch box was mounted on the forward bulkhead in the steering engine compartment. The switchbox vibrated on the bulkhead like a mass on a diaphragm, Trace N, causing the screws holding the switchgear to loosen. The feeder cables shorted to earth and the fuses blew.

In order to increase the natural frequency of the bulkhead the switchbox was removed and mounted on vertical channel bars. A crack in the bulkhead near the deck was repaired by welding. The vibration was eliminated.

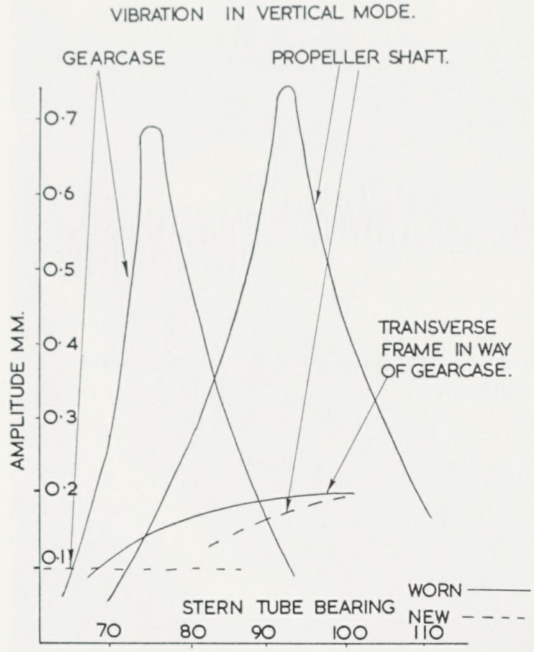
Trace N

Steering Flat Bulkhead. Tanker

EXAMPLE 13

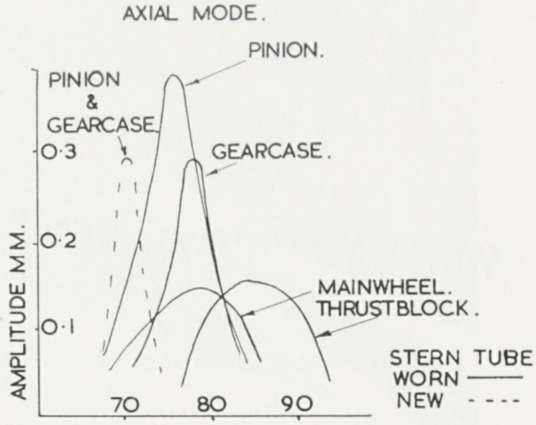
This example, which concerns propeller excited gearcase vibration, could perhaps be justifiably termed an "engine vibration", and not a "hull vibration". However, since the exciting force was generated by the action of wake variation on the propeller, and the vibratory forces were transmitted through the hull to the gearcase, causing it to vibrate on its seating against the hull, the example has been included in local hull vibration. It appears to be one of the many cases where hull and machinery combine to give a mass-elastic system complete with exciting force.

The secondary pinions of a turbine-driven tanker 660 ft. in length, deteriorated after they had been in service for about four years. The vessel had recently operated continuously on long voyages at approximately 75 r.p.m. Investigations were carried out on board the vessel before and after dry docking when the sterntube was rewooded and the bearing clearance reduced from 8 mm. to 1 mm. Figs. 40a, 40b and 40c show resonance curves taken from the gearcase, hull, thrust block and propeller shafting. The vibrations occurred at propeller blade frequency, i.e., 5 × shaft r.p.m.



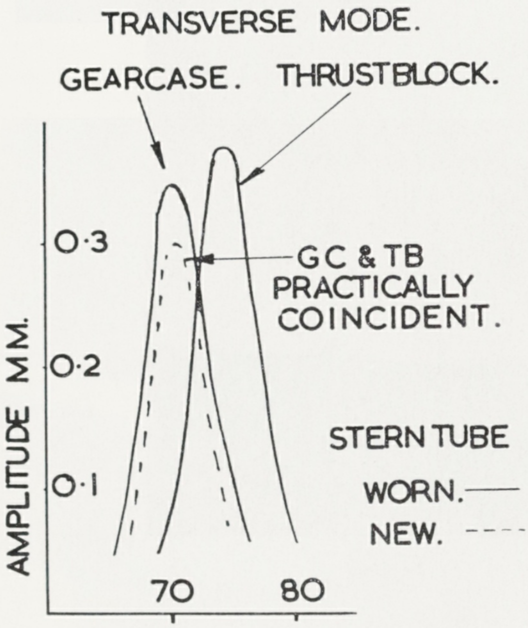

PROPELLER RPM. FIG. 40A.

Showing the reduction in gearcase vibration when the stern tube bearing clearance was reduced from 8 mm. to 1 mm. The transverse frame ceased to vibrate




PROPELLER RPM. FIG. 40C.

No vibration was observed on the mainwheel and thrust block when the stern tube bearing was renewed.




PROPELLER RPM. FIG 40B.

It is considered that the local vibration of the gearcase in the vertical mode, Trace P, was excited by forces generated by resonant propeller whirl even though the resonant frequency of the gear-case was low on the flank of the resonance curve for propeller whirl (*see* Fig. 40a). The gearcase vibrations in the transverse and axial modes were probably propeller excited by torque and thrust variation at the gearwheel journal and thrust block respectively.

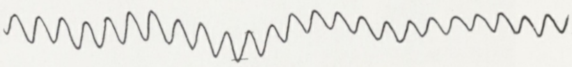
At the time of writing a watch is being kept on the gears to see whether the deterioration has ceased now that the critical speeds are avoided and the propeller shaft bearing weardown is not allowed to become excessive.

Trace P

Gearcase Vertical. Worn lignum vitae in stern tube.

Example 14

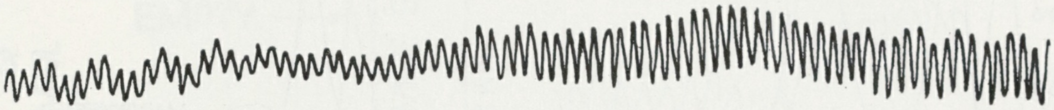
Certain samson posts on a new ship vibrated excessively when the propeller blade frequency coincided with the natural frequency of the posts, Traces Q1, Q2 and Q3. Hull vibration at the base of the posts was negligible and the propeller blade clearances were acceptable. One of the posts failed (Figs. 41 and 42), and cracks appeared at stress raisers on others (Fig. 43). It was proved by experiment that wire rope stays would eliminate the vibration (Fig. 44). Recommendations were also made to eliminate the stress raisers. This example illustrates how a very small exciting force can generate dangerous amplitudes when the damping force is small.



Trace Q1

Trace Q2

Samson Post Vibration. Askania & Geiger



Trace Q3

Samson post vibration at propeller blade frequency. Vibration of hull at base of samson post was negligible

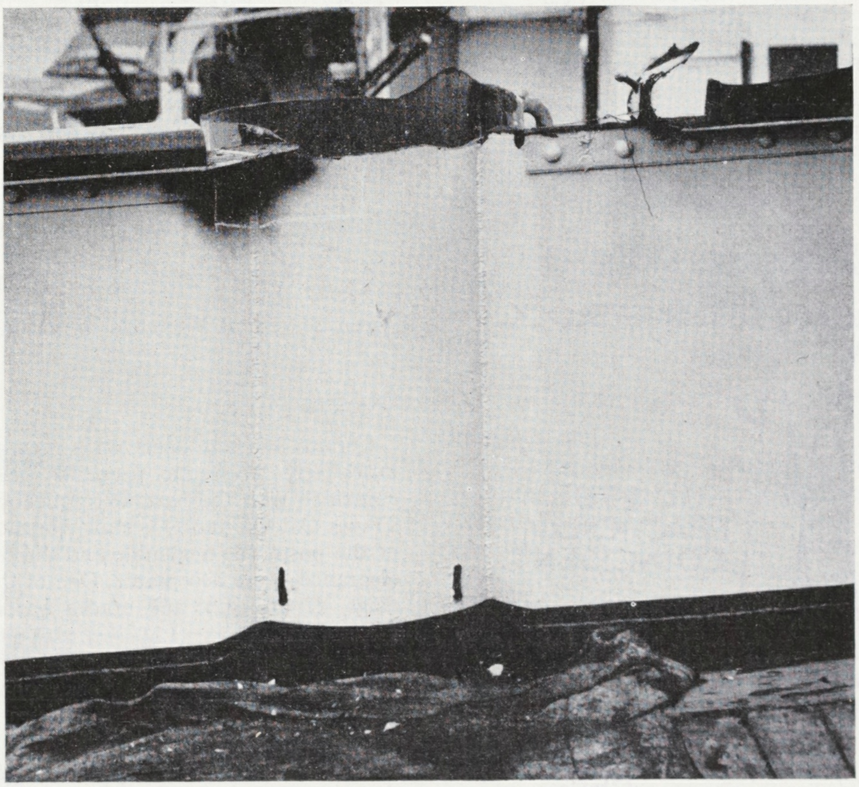


Fig. 41

Stump of fractured samson post. Fracture occurred in way of bridge rail angle

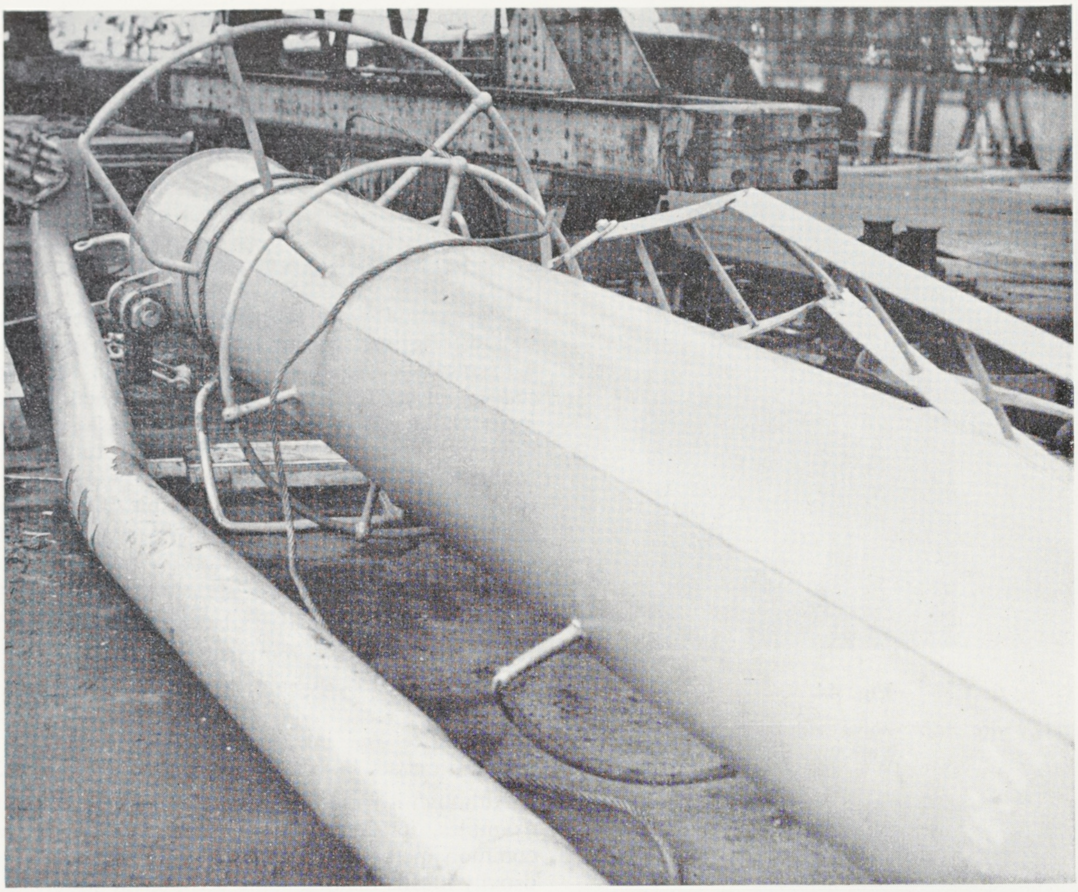


Fig. 42
Fractured samson post taken ashore

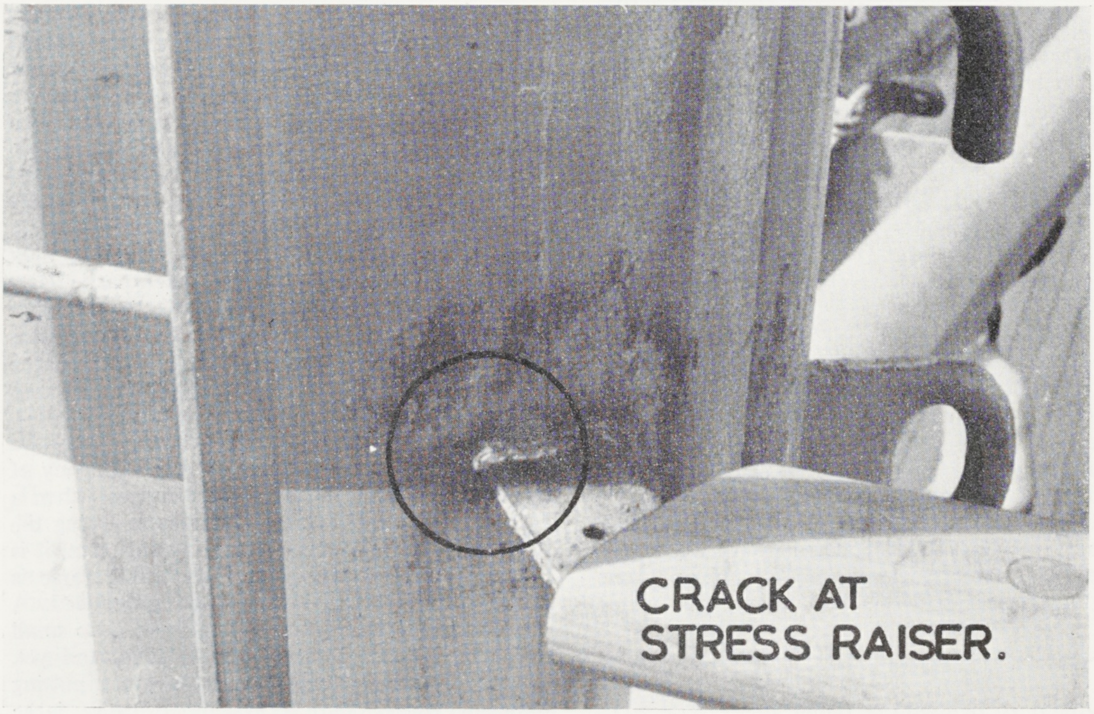



Fig. 43
Crack in stress raiser formed by welding bridge rail angle to samson post. Timber removed to show angle bar

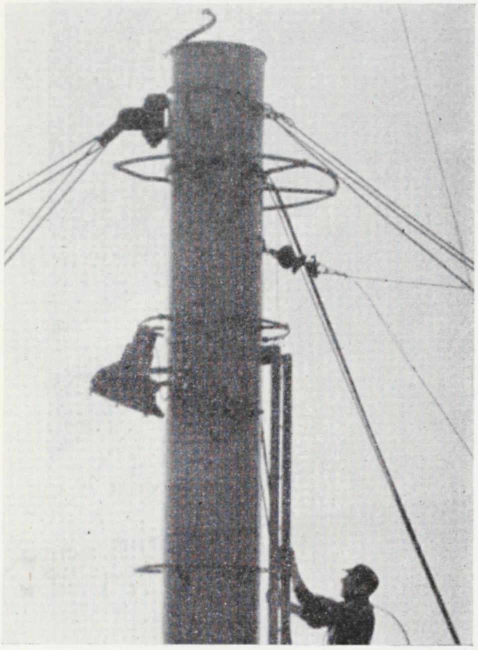


Fig. 44

Temporary wire rope stays eliminate samson post vibration

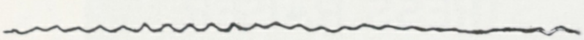
EXAMPLE 15

The front casing of the watertube boiler in a new ship vibrated violently at propeller blade frequency, and carried with it a ladder leading into the stokehold which was stayed to the casing. The chief engineer shored heavy wooden planks across the casing, and this slightly reduced the amplitude of the vibration until the wedges became slack.

When the planks were removed the casing and ladder vibrated again, but when the ladder stay was removed, the vibration was eliminated.

EXAMPLE 16

A large turbine - driven tanker suddenly developed pronounced transverse vibration at propeller blade frequency at the stern when running near full speed. The rudder head vibrated and hammered when the hull vibrated. Two plates were missing from the rudder when the vessel dry docked, and the pintles were loose in their tapered holes in the rudder. Calculations of the natural frequency of the rudder on its stock in the torsional mode indicated the possibility of resonance at propeller blade frequency for normal service speed when the rudder was full of water, but not when it was empty. The calculations were supported by measurements, Trace R. It appeared that the rudder had suddenly filled with water when the plates cracked and the increase in mass had lowered the natural frequency to propeller blade frequency. When the rudder was repaired it was filled with a light plastic foam to prevent ingress of water should it crack again. The vibration was eliminated.



Trace R

Rudder Stock Torsional. Tanker

## SUMMARY AND CONCLUSIONS

The examples quoted in these notes were chosen to illustrate how one or more vibratory forces in a mass-elastic system can be modified in order to reduce unwanted vibration. As mentioned in the introduction, there are only four fundamentally different vibratory forces and hence only four fundamentally different approaches to the solution of any vibration problem. The table below indicates how often each approach was used in the 16 examples numbered in the text.

| | |
|---|---|
| Spring force ; stiffnesses modified ... ... | 7 |
| Damping force ; increased (damper repaired) | 1 |
| Inertia force ; masses modified ... ... | 3 |
| Exciting force ; frequency changed or force reduced ... ... ... ... ... | 3 |
| Spring force and inertia force ; stiffnesses and masses both modified ... ... | 2 |

Although it would be easy to collect 16 different examples, it appears from these that the most common method is to alter the spring force ; this usually means making some component stiffer, i.e., bigger and stronger. Even if it is not the commonest method, it seems to be the one that is most often misapplied. After all, when part of a ship or engine breaks in service, there is something very attractive in the idea that its replacement should be stronger. But size is no guarantee against resonance. If a stronger component is fitted its stiffness should be such that resonance does not occur.

Reduction of vibration by modification of inertia forces is less frequently adopted, probably because it can entail a fairly large increase in weight. The designer usually makes things as light as possible. This approach is, however, particularly useful for hull vibration when the vessel is in ballast, since then it may be possible to redistribute the ballast and hence vary the inertia forces. As with spring forces, a variation in inertia forces may increase instead of reduce the vibration.

Modification of an exciting force may be accomplished either by removing the frequency of the force from the resonant frequency, as when a barred speed range is applied, or by reducing the magnitude of the force. Here, it would seem, it is impossible to go wrong ; if the exciting force is reduced the vibration must also be reduced. A problem arises when the exciting force is so small that it is difficult to locate and define, and yet, over a number of cycles, is capable of putting sufficient energy into a system to cause large amplitudes. Resonant structures collect energy remorselessly. If the damping is small, a small

exciting force can cause a disproportionate amount of trouble and it is then that modification to a stiffness may be the simplest solution. Indeed, it appears that in systems containing negligible damping, e.g., a steel mainmast tuned to propeller blade frequency, the amplitude is limited by a change which occurs in the stiffness at large amplitudes; the stiffness is non-linear.

Although damping exists to some extent in all vibrating systems, the deliberate introduction of damping forces seems to be practically confined to transmission systems which are susceptible to torsional vibration. In other systems the introduction of damping forces is largely fortuitous, as when a vibration-prone hull is loaded with bulk sugar, grain or similar cargo instead of, say, steel ingots.

It therefore appears that the reduction of unwanted vibration resolves into the problem of which type of force to alter; before a decision can be taken it is necessary to have some idea of the exciting force, its origin, magnitude and frequency, the resonant frequency of the vibrating system, the values of the stiffnesses and masses taking part, and any damping forces. If these can be estimated the rest is reasonably straightforward.

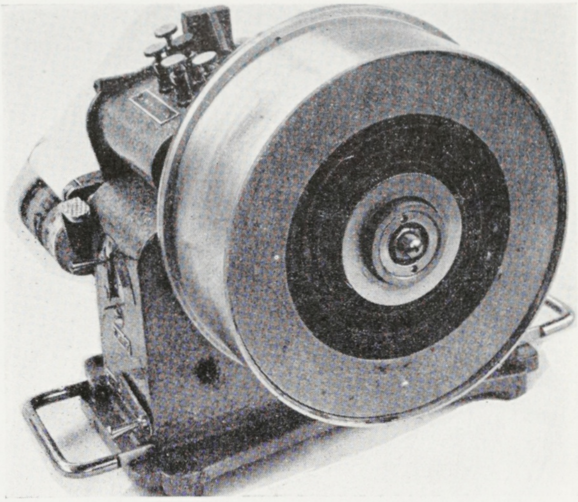


Fig. 45

Spring-mounted seismic mass of Geiger Torsiograph

# APPENDIX

**The Geiger and Askania Vibrographs**

Many different instruments, of which the Engineering Investigation Department possesses a full range, have been devised to measure the frequency and amplitude of vibrating systems. A separate paper would be required to describe all these instruments, but as these notes have been illustrated with traces from the Geiger and Askania vibrographs, brief descriptions of these two instruments are given below:—

1. The Geiger

Here a mass is attached by a spring to the body of the instrument (Fig. 45). When used as a torsiograph, the light, outer pulley is driven by a belt from the shaft under experiment and follows the fluctuations in angular velocity of this shaft. The mass rotates with constant angular velocity and the relative motion between mass and pulley actuates the lever shown inside the pulley (Fig. 46). This motion is transmitted to the lattice pen shown in Fig. 47 and a record is obtained on the paper. The instrument is calibrated by driving it from the pulley shown on the left hand side of Fig. 48. A Hooke's joint is incorporated in the pulley drive in order to give a known speed fluctuation and thus simulate torsional vibration. The Hooke's joint can be turned through a small range of angles marked on the quadrant below the pulley. Since the angle is known, the variation in velocity ratio is known and hence the movement of the pen on the paper can be measured for known fluctuations in angular velocity.

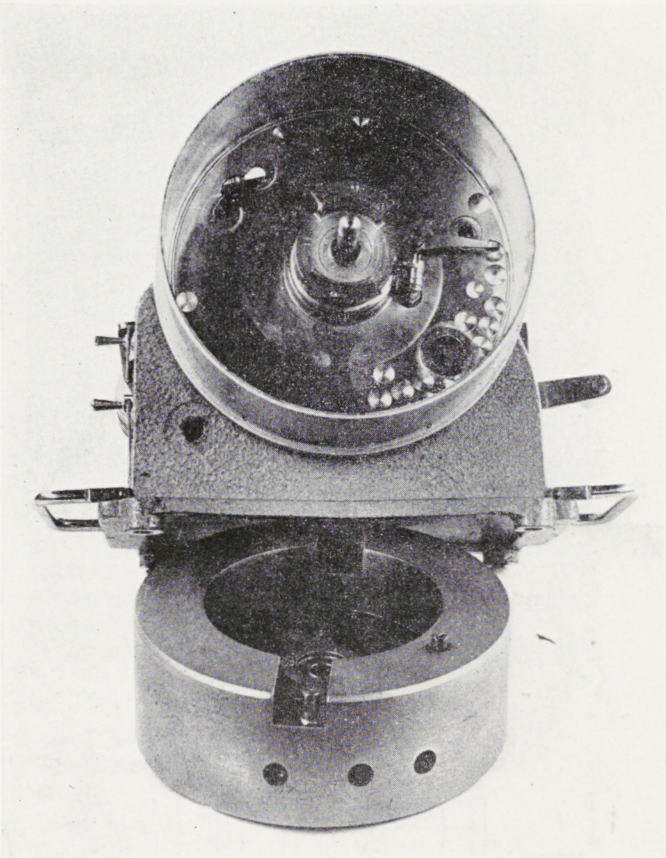


Fig. 46

The lever inside pulley is operated by relative movement between pulley and mass. Movement transmitted to pen seen in Fig. 47

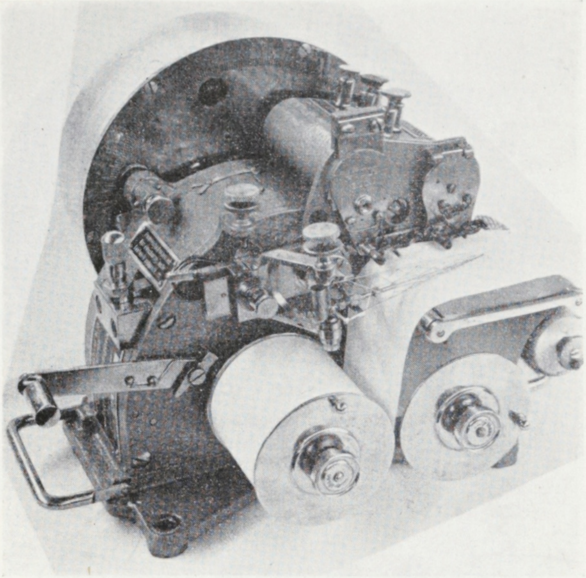


Fig. 47

Lattice pen produces record on moving paper

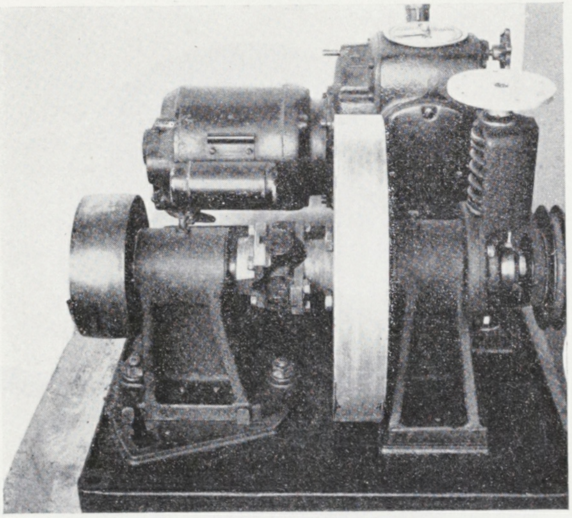
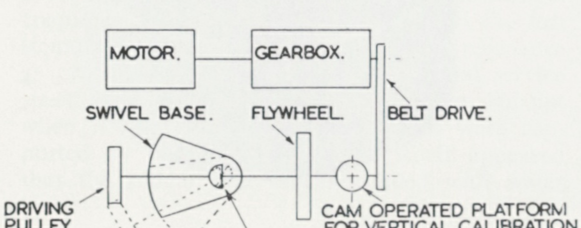


Fig. 48

Instrument used to calibrate Geiger Vibrograph




SKETCH OF CALIBRATOR.
FIG 48A.

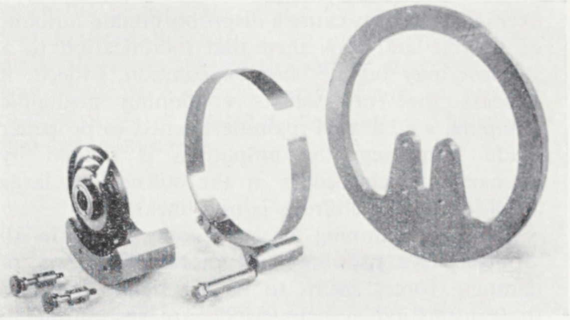


Fig. 49

Segmental seismic mass and auxiliary mass used to convert Geiger Torsiograph to Vibrograph for recording linear vibrations

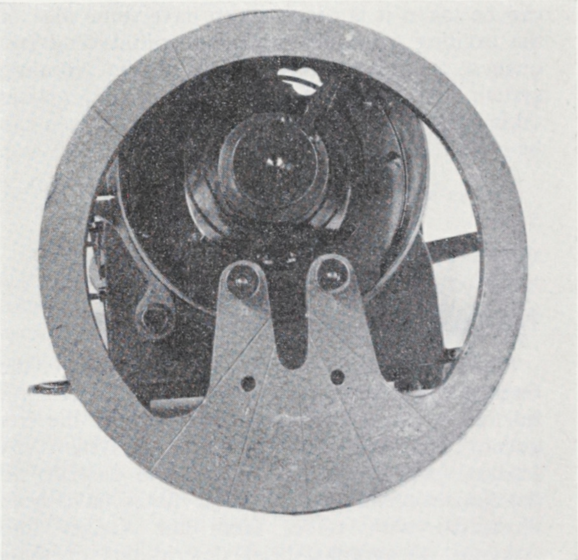


Fig. 50

Segmental and auxiliary masses fitted

When used as a vibrograph the circular mass is replaced by the segmental mass in Fig. 49 and the light pulley is clamped by the circular steel band. The additional mass shown on the right-hand side of Fig. 49 can be attached to the segmental mass as shown in Fig. 50; this reduces the natural frequency of the instrument and enables lower frequency vibrations to be recorded.

Fig. 51 shows the instrument measuring horizontal hull vibration on a large cargo vessel. To record vertical vibration the masses would be rotated through 90° and the spring tension re-adjusted. A half-second electrical timer is connected to the instrument which marks the paper and enables a check to be made on the frequency of any vibration recorded.

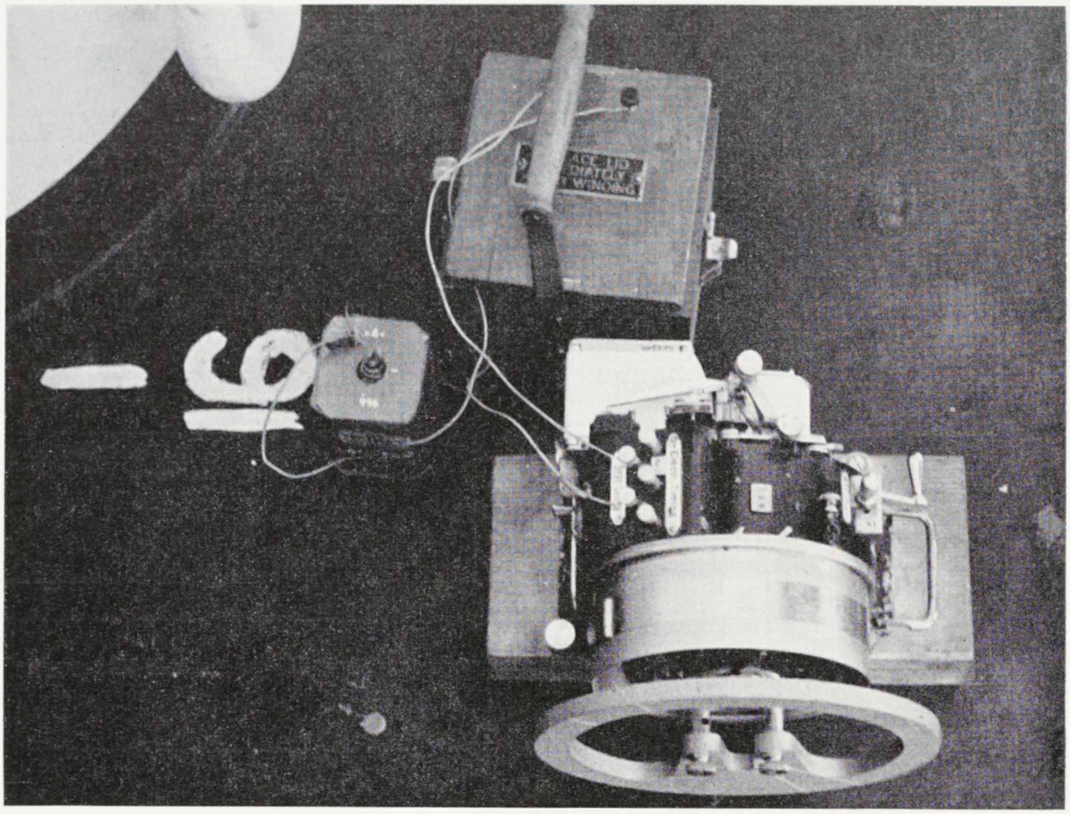


Fig. 51

Vibrograph in position on the deck of a cargo ship

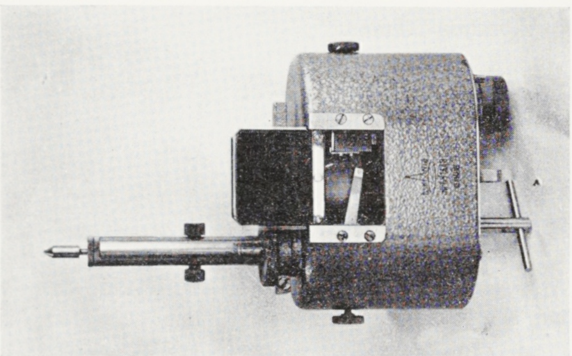


Fig. 52

Askania Vibrograph

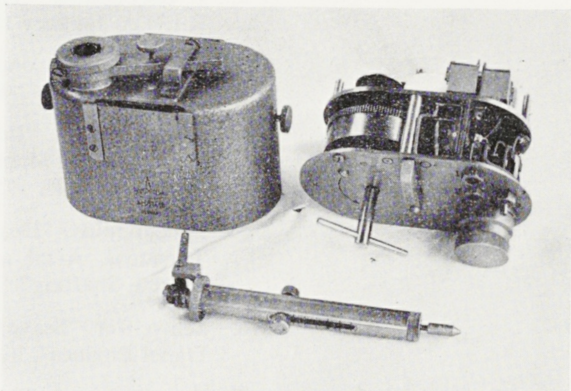


Fig. 53

Main components of Askania Vibrograph

2. The Askania

This instrument (Fig. 52) consists of a spring-loaded pointer actuating a stylus on waxed paper. The paper is driven at constant speed by clock-work and a second timer is incorporated. The three main parts are shown in Fig. 53.

Fig. 54 shows the instrument being used to record vibration at the base of a ventilator. The instrument should be held in a fairly relaxed grip as indicated.

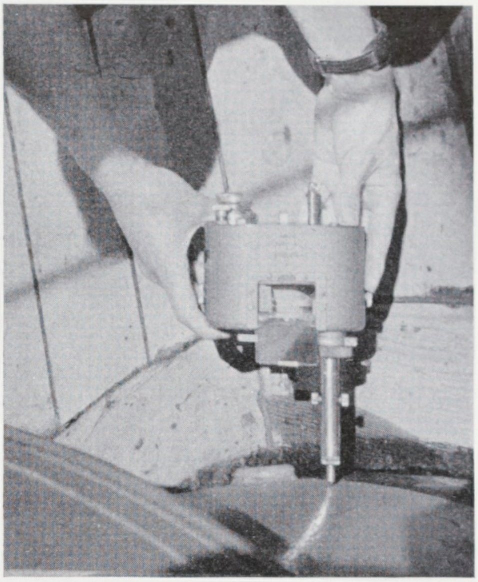


Fig. 54

One method of holding Askania Vibrograph

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Printed by Lloyd's Register of Shipping at Garrett House, Manor Royal Crawley, Sussex, England

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# Lloyd's Register Staff Association

Session 1960 - 61

Paper No. 2

## Discussion

on

Mr. A. R. Hinson's Paper

# SOME NOTES ON VIBRATION PROBLEMS

LLOYD'S REGISTER OF SHIPPING

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Discussion on

Mr. A. R. Hinson's Paper

# Some Notes on Vibration Problems

## Mr. J. H. Milton

It is my privilege to open the discussion to-night. I am very proud to do this as Mr. Hinson is a member of my Department, and I feel sure that after reading this paper, you will agree that, when it comes to vibration, he knows what he is talking about and how to talk about it. In fact, I would go so far as to say that this paper should not be confined to the Staff Association, but should, for the sake of Lloyd's Register in general and the Engineering Investigation Department in particular, be read if possible at other technical meetings both at home and abroad. This would, I think, show other classification societies that Lloyd's Register do not only deal in classification, but are in a position to give expert assistance on baffling problems to Owners, Ship and Engine Builders, etc.

Mr. Hinson has covered his subject very comprehensively but there are two points which I think could be further discussed.

Firstly, as roughly 50 per cent of the examples of vibration quoted in the paper are propeller-excited, there would appear to be ample room for improvement in propeller and after body design to obviate vibration.

Secondly, vibration appears to be more prevalent in welded than in riveted ships, and also in vessels with engines aft. The Author's views and those of our Ship colleagues present on these two points would be very welcome.

## Mr. S. Archer

The Author has contributed valuably to the not inconsiderable store of information and knowledge in the Society's archives on this highly important subject and I would add my congratulations and thanks to those of, I am sure, a great many of his colleagues for giving us such a practical, wide-ranging and stimulating paper. I am confident that it will prove to be one of those comparatively rare works which most surveyors, ship or engine, will want to have close at hand for ready reference in their day-to-day problems for many years to come.

In his introduction the Author lists four fundamental methods of overcoming vibration, of which two (Nos. i and iii) act against resonance by changing the natural frequency of the system and the other two by reducing the unfavourable effects of existing resonance. A fifth method could perhaps legitimately be added to these, which in effect achieves the same result as Nos. i and iii, namely, a change in speed or frequency of excitation of the moving part responsible for setting up the vibration. For example, changing the number of blades of a propeller, increasing the pitch and/or area of a propeller in order to lower the service speed below an offending critical.

In applying any, or all of these approaches, it is important to bear in mind that whatever changes are made *may* conceivably adversely affect other modes of vibration either in the same type of vibration, or in another type as, for example, torsional, axial and transverse for shafting. Cases are by no means uncommon in vibration problems of jumping from the "frying pan", if not actually "into the fire", then at least into another "frying pan"! Could the Author instance any such cases known to him personally, preferably of course on ships not classed with L.R.!!?

Another pitfall, well brought out in the Author's examples, is the danger of transferring vibration from one location to another when attempting to eliminate vibration by stiffening or staying methods. It is important that whatever part of the structure is chosen as an anchorage should be really and truly rigid and/or massive. As the Author rightly points out, "No stiffening may be better than too little".

On the subject of engine seatings and their resonances, I recall a case of two six cylinder, 4-S.C. auxiliary engines running at 600 r.p.m., arranged abreast of each other and with their axes fore-and-aft. Severe transverse vibration was set up from piston side thrust effects and this made itself felt most unpleasantly as lateral panting of alleyway bulkhead plating on the upper deck level. The vibration was made more noticeable and unpleasant by the "beating" effect between the two engines concerned and as some passenger accommodation was affected, the Superintendent was greatly concerned. After considering and rejecting many possibilities, it was finally decided to cut through the transverse bearers supporting the engine bedplates the cuts being made vertically from above and into the oval lightening holes in the bearer web plates between the engines. Thereby, the natural transverse frequency of each engine about its seating was sufficiently reduced to avoid resonance at the normal service speed of 600 r.p.m. and this "did the trick!"

The material included by the Author on the important subject of propeller-excited vibration is very well chosen and up to date. The model results of shaft bending moments shown in Fig. 11c, ref. 8, are highly revealing and demonstrate clearly, at least qualitatively, the undoubted

inferiority of five-bladed propellers, compared with four- or six-bladed, as regards transverse bending excitation of screw shafts. Fortunately, there is evidence that the thrust and torque variations, and therefore presumably also the shaft bending effects, in the full size propeller assembly at sea may be appreciably less than predicted by model tank tests in smooth water. Thus, in one case reported by Nitzki of A.G. "Weser" (Ref. A) the full-scale torque and thrust variations were only 60 per cent and 80 per cent of the model results, respectively. Nevertheless, model tests are valuable for indicating trends and for comparative purposes, e.g., assessing the effects of different aperture clearances and shapes of stern frame, after body form, etc., etc.

On the relative rates of wear-down as between screwshafts driving four-bladed and five-bladed propellers, a recent investigation by C.E.S.R. based on 20 ships (ten of each) exceeding 10,000 s.h.p. in propelling power gave the following figures as average annual wear-down rates:—

| | |
|---|---|
| Four-bladed screws | 0·052 inches |
| Five-bladed screws | 0·071 inches |

or about 40 per cent greater rate of wear-down for the five-bladers. However, in both cases the average period between re-wooding was no more than about two years eight months. Thus, the gain due to fitting a four-blader instead of a five-blader seems to have been insufficient to allow the shafts to go for a further three-year period without re-wooding.

In Example 9 the Author describes a bevel pinion failure in the drive to a Voith-Schneider propeller and suggests that the cause of failure was torsional vibration. Whilst this may well have been a contributory cause, Fig. 18a shows vividly the effect of inadequate fillet radii, an unfortunate characteristic of some German reduction gears, even to-day. Could the Author state the material of the pinion and indicate whether, as in a series of five recent ferries fitted with V-S propellers whose gears also failed catastrophically, the hardening of the pinion teeth was by the flame process, or alternatively, by nitriding or case-hardening? Flame-hardening of gear teeth is, of course, no longer accepted by the Society, in consequence of these and other similar failures.

The Author's experiences with hull vibration are both varied and informative, and he is to be congratulated particularly upon his ingenuity and perseverance in producing Figs. 28 A to F and 29 for rapid estimation of hull criticals for tankers. These must have demanded a tremendous amount of work and it is to be hoped that the Todd and Marwood type formula (as modified by Fraser-Smith) on which they are presumably based, is the best available for the purpose. Could he quote some actual data of measured examples so that colleagues could judge for themselves the order of accuracy obtainable? It is noted the Author intends to extend this work to cover dry cargo ships also and presumably this will be an even more difficult task having regard to the much greater diversity of structure, form and loading, etc., in such vessels.

On the subject of permissible limits for hull vibration amplitudes it is observed from page 28 and Fig. 36A that the Author suggests these should correspond to constant limits of acceleration, the value for possible hull damage being assessed at three times that given for crew comfort under vertical vibration. Incidentally, although not stated by the Author, it is presumed the figure of 3 ft./sec.$^2$ refers to that measured at the after antinode, which is usually the maximum for normal modes. These limits, are, I believe, fairly widely accepted in the industry in this country and may well be reasonably satisfactory so far as hull damage is concerned, although even there I know of no substantiating experimental or other published works. Are any known to the Author? The problem of crew, and especially passenger, comfort is even more difficult to bring to rule. For one thing, the human body does not exhibit the same degree of tolerance to acceleration at all frequencies and in this respect resembles the behaviour of the human ear whose assessment of equal loudness varies in a somewhat complex manner with frequency and is by no means constant. What little evidence there is suggests that, at least under fairly low frequency vertical vibration, the body can tolerate increasing acceleration as the frequency rises. I have plotted all the data I have been able to find on the diagrams (Figs. 1 and 2) in terms of amplitude, frequency and acceleration and it will be seen that whilst there is by no means exact unanimity concerning the thresholds of perception and unpleasantness, there is at least qualitative agreement as to their general trend with frequency. One factor, perhaps not generally appreciated, is that under vertical "whole body" vibration, human beings exhibit resonance within the range of 200 to 300 cycles per minute ($3\frac{1}{2}$ to 5 c.p.s.)*. This, of course, comes well within the range of propeller blade frequency excitation and may partly account for the reduced human tolerance of vertical vibration over this frequency band and increasing tolerance above it. It is clear that there is need for much further experimental work in this field and it would be interesting to have the Author's views on the subject. The Author's Figs. 36A, B and C, giving in graphical manner the relationships between amplitude, frequency and acceleration are both practical and convenient.

The overall picture presented by Mr. Hinson is that, given a real appreciation of fundamental principles, the right instruments and the ability to use them effectively, and a fair slice of engineering commonsense and insight, shipboard vibration phenomena will shed much of their "mystery". But then, of course, it would for most of us be easier and probably safer to leave it to Mr. Hinson!

Ref. A. NITZKI "Resistance and Propulsion of High-Powered Single-Screw Vessels", European Shipbuilding No. 3, 1959.

* "Some Physiological Effects of Low-Frequency, High-Amplitude Vibration", by M. A. Schmitz & C. A. Boettcher. ASME Publication No. 60-PROD-17.

### Mr. J. Burton Davies

The Author has given us a very comprehensive paper on vibration and has added to its value by quoting specific cases.

The Society has been called in increasingly during the past 10–15 years to examine vibration problems, and it would be interesting to know whether more and more ships are experiencing vibration trouble, or whether owners are now recognising a problem which has always existed. It may well be that the problem has been accentuated by the arrival of the all-welded ship coupled with the popularity of the diesel engine.

Under the heading "General Hull Vibration" the Author refers to the desirability of having a quick method of estimating the probable mode of vibration likely to be encountered and has drawn a large number of charts based on Bunyan's formula. The drawing of these charts has obviously involved a great deal of work, but I wonder whether this is entirely justified. The formula itself does not pretend to be accurate, although I agree it is extremely useful for estimating purposes when only the main dimensions are known. The use of these charts involves interpolating both in the charts and between two separate charts, and this introduces a further possible inaccuracy into an already approximate formula. As the formula is relatively simple, I think it would probably be as easy to use the formula as to use the charts. I appreciate that the Author has labelled each chart "approximate only", but I think that readers might get a false idea of their accuracy, which is not so likely to occur if the formula itself is used, so that the particulars used are readily appreciated.

The Author also quotes a horizontal acceleration of 3 ft./sec.$^2$ as being the figure usually taken for the maximum acceptable for the avoidance of damage to the hull. I would again like to sound a word of warning that this can only be taken as true in a very broad sense.

### Mr. A. E. Toms

In Mr. Hinson's excellent paper there are many points worthy of discussion, but I intend to confine myself to three of them.

On page 7, in reference to resonant propeller whirl, the Author recommends the method in Panagopulos' 1950 paper for estimating the natural frequency. It should be noted there is an error in this method. Panagopulos reduces the stepped shaft system to that of an equivalent shaft. A perusal of Fig. 13 in the present paper will indicate that the overhung section aft of the centre of the sterntube bearing is very important. In the Panagopulos formula with special reference to the expression for the vertical movement of the propeller, i.e. $mb^2\left(\frac{b}{2}+\frac{l}{3}\right)$ the value of b outside the bracket should be the *actual* length of the overhung section and *not* the equivalent length.

In one case where a Firm experienced the wear patterns as shown in Fig. 12 and the shaft was cracked at the top of the cone they followed the method of Panagopulos slavishly and calculated the critical speed to be approximately 50 per cent of the service speed. By an exhaustive analysis of the method and a more logical approach to the masses and bending stiffnesses involved, it was possible even with a simplified formula such as Panagopulos' to calculate the critical speed to occur at the service r.p.m.

In 1954 Panagopulos published a paper giving the results of tests on the s.s. *Chryssi*. The calculations of frequency are not shown in that paper although the 1950 formula is again recommended. If these calculations are carried out, it will be found that the frequency obtained is some 20 per cent below that measured.

On page 15, Mr. Hinson refers to twin spring couplings. About nine years ago, I was involved in the acceptance of what I was informed at the time was the first of this type submitted to the Society. For my sins, presumably on the assumption that I should sink or swim with my opinions, I was sent on the trial trip to listen for possible gear hammer. It acted exactly as hoped and to the best of my knowledge not even a spring has had to be replaced in some eight and a half years' service. Judging by Mr. Hinson's remarks and Trace K in Fig. 25, there appears to have been some trouble in later versions of this type. It would be of interest if he could give some more details on the causes and cures of such troubles.

On page 39, in the "Summary and Conclusions", Mr. Hinson states "the deliberate introduction of damping forces seems to be practically confined to transmission systems which are susceptible to torsional vibration. In other systems the introduction of damping forces is largely fortuitous". Here he is being unnecessarily modest. Commander Goodwin in a recent paper to the Institute of Marine Engineers described a resonance changer fitted to the thrust block in which he placed great store on the damping capacity for axial vibrations. In discussions with Mr. Hinson on this device I have discovered he did a deal of work in the design stage before entering this Society. Recently we have also had the very small Fiat "dash pot" device fitted to the forward end of the crankshaft to damp out axial vibrations. I hope that Mr. Hinson will agree with me that we are learning and progressing, even if only slowly.

### Mr. G. S. Pidd

The Author's theme of analysis of vibration into its ingredients of spring, damping, inertia and excitation forces has done much to make this paper more palatable to all members of the Society, many of whom have an ample sufficiency of indigestible problems of their own. It is a welcome paper which contrasts favourably with those of the type in which Authors seem deliberately to make their subject more complicated by the introduction of specialised terminology.

The exciting force itself usually has a magnitude, frequency and phase of which the frequency

is very useful in helping to trace it to its source. To measure the frequency of a vibration it is advisable to use some type of instrument because vibration diagnosis using the state of one's rheumatics is, nowadays, somewhat discredited.

A common source of perplexity arises from the difference between:—

(a) The forced frequency, which with the diesel engine is often the number of firing impulses per minute.

(b) The natural frequency which depends mainly upon the spring and inertia forces, which is in evidence when a bell is struck with a hammer.

A forced vibration vibrates at the forced frequency but reaches the largest amplitude when this forced frequency coincides with the natural frequency, which is a phenomenon known as resonance.

It is a popular misconception that the existence of resonant speeds within the operating speed range is only caused by the stupidity of the designer. One of the first investigators of this process of reducing vibration was King Canute, but it will be remembered that he did not have much success.

Most Engineers are restricted in design problems by the cost factor. Noise, which is another type of vibration, seems to be giving all the aircraft engine manufacturers a headache, not to mention others who live near an airport.

Thus although vibrations can be expressed mathematically in imaginary quantities, their results are real enough to be perceived by all.

## Mr. J. S. Shand

We are indebted to the Author for this addition to the transactions on a subject which has been assuming ever-increasing importance of recent years, and the well-balanced choice of examples indicates some of the forms in which vibration displays itself in shipbuilding.

In the section dealing with propeller whirl, Fig. 11c rightly shows that five-bladed propellers have a much larger variation in moment of thrust about horizontal and vertical diameters of the propeller disc than four- or six-bladed propellers, and so are more likely to give rise to shaft whirl. Before condemning the five-bladed propeller, however, on this one count it might be added that its variations in thrust and torque are less than for other propellers and these have been known to cause vibration of shafting and machinery. In addition, since the optimum diameter of a five-bladed propeller is less than that of three- or four-bladed propellers, then, for a given stern-frame aperture, greater tip clearance is obtained, while the exciting force itself will also be reduced owing to the larger number of blades. The latter two characteristics are obviously of great importance with regard to hull vibration and in fact have been utilised on occasion in conjunction with the accompanying change of exciting frequency as a cure for hull vibration investigated by the Society.

Figs. 16A, B and C in the same section show increase in bending moment in the tailshaft caused by slope-boring, but since these diagrams are drawn for point loading, while the purpose of the slope-boring is to spread the load it would seem that the diagrams A and B should be curved, rather than linear between the forward and after extremities of the stern-tube bearing surface thus reducing the value of maximum bending moment.

Figs. 28A to F for obtaining an estimate of the two node vertical critical frequency have been very cleverly devised, but one wonders whether there is any advantage in following through the graphical procedure, twice for any particular draught, as opposed to calculating once by slide rule from the formula on which the charts are based.

In reducing hull vibration by means of changing mass distribution it is felt that some reference could possibly be made to the difference between adding mass at the most effective positions additional to the original loading, and merely redistributing the existing loading. It has always appeared to the writer that while adding extra weight affects frequency and amplitude, the main benefits of weight redistribution lie in amplitude reduction rather than frequency alteration. The Author's comments would be appreciated.

The problem of permissible limits for general hull vibrations is rather a thorny one and the figures quoted in the paper have had a certain amount of acceptance, but it is felt that perhaps from a comfort aspect higher accelerations are tolerable at higher frequencies and at very low frequencies, and that the permissible acceleration might be better expressed as a curve than as a straight line. The adoption of a fixed value of acceleration permissible from a structural damage aspect, too, raised some doubts since the same value of acceleration can undoubtedly give rise to greatly differing stresses in different ships.

In closing I should again like to thank the Author for the considerable efforts involved in an extremely interesting paper.

## Mr. J. M. Jennings

Mr. Hinson has produced a very readable and well-illustrated paper which gives useful information to those concerned with vibration problems whether occasionally or permanently. I would, however, like to make some minor criticism of the presentation of the Geiger and Askania vibration records as some of the explanations of the traces are rather sketchy.

Mr. Hinson has made an important point in giving examples of severe gear hammer not always obvious to the ear. I would like, therefore, to amplify his examples with a brief description of methods of detecting torsional vibration by means of electrical resistance strain gauges.

Fig. 3 shows a selection of strain gauges. The wire or foil grid and the connections to each can be seen in three of the gauges. If the gauge is bonded to a material with a special "strain gauge cement" and the material is stressed along the axis

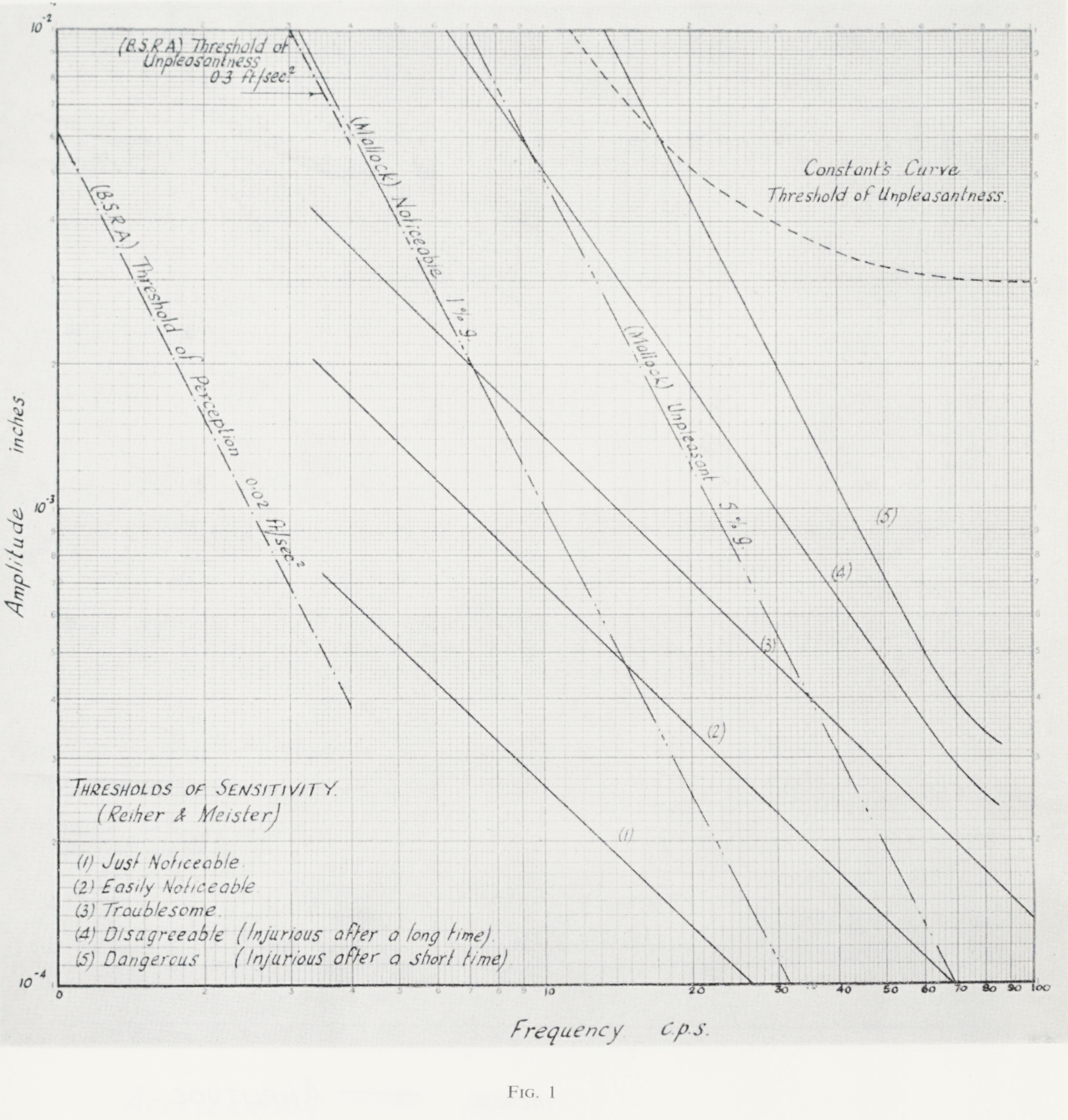
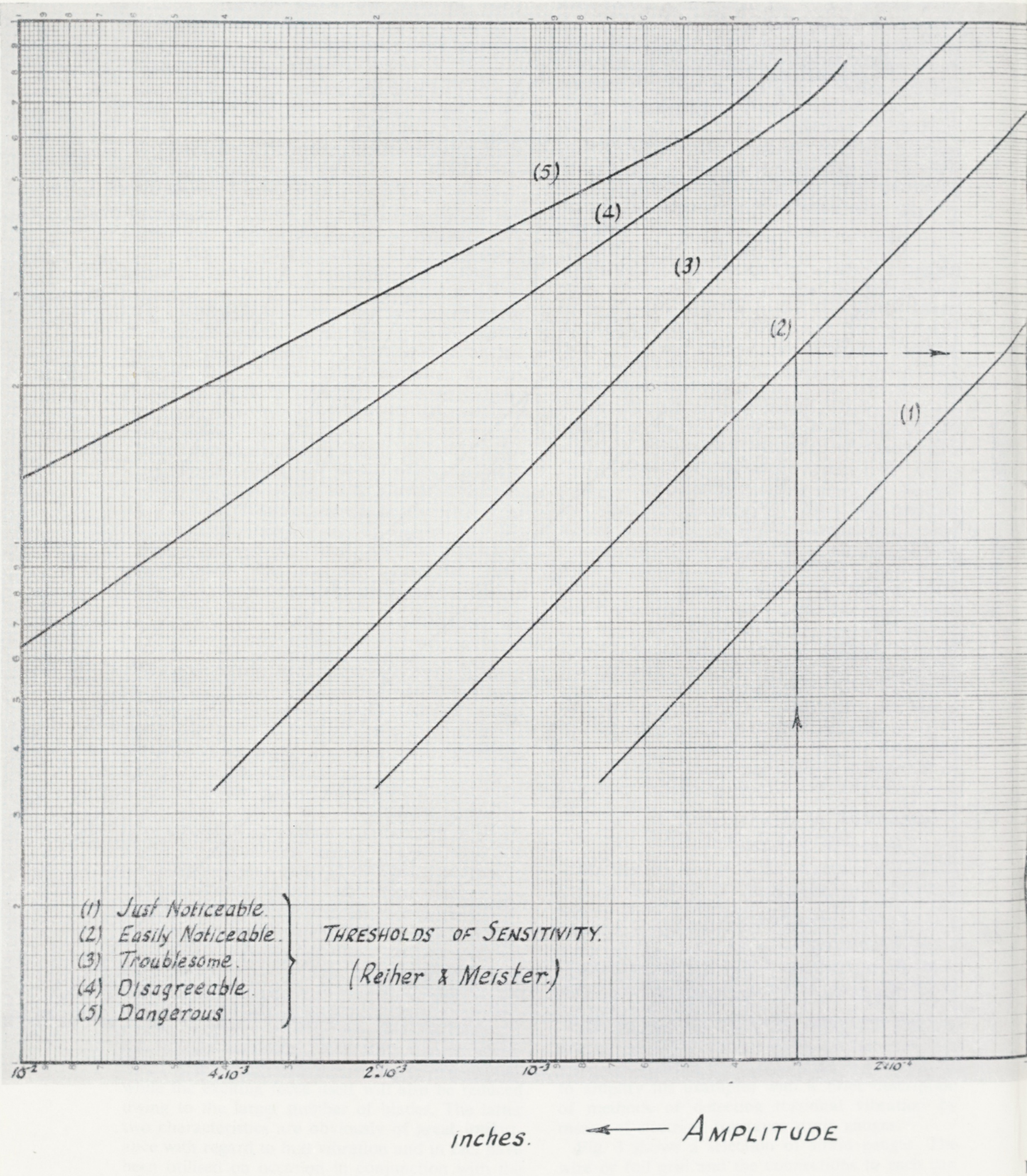
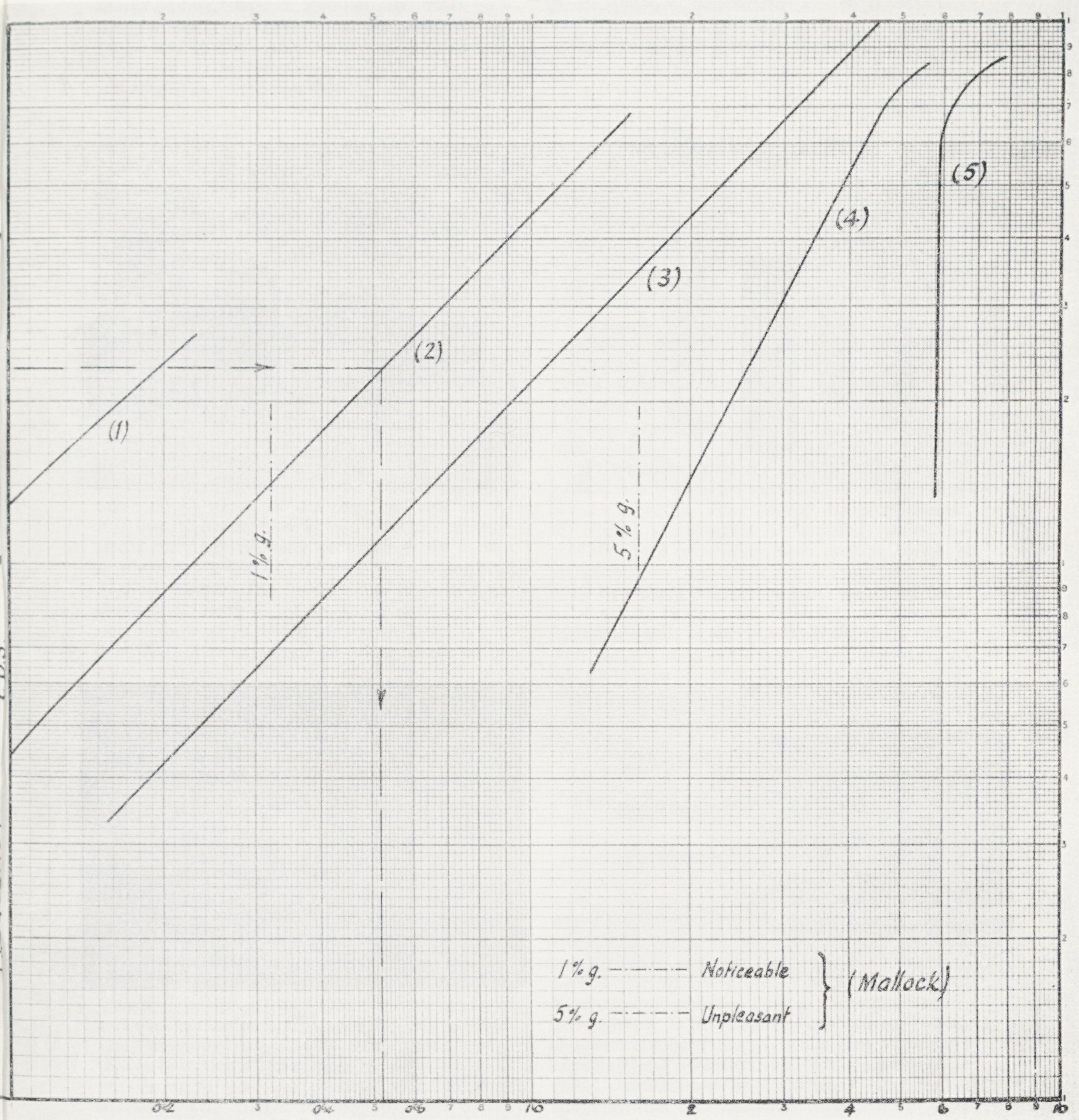

(B.S.R.A.) Threshold of Unpleasantness 0·3 ft/sec.²
(Mallock) Noticeable 1% g.
(B.S.R.A.) Threshold of Perception 0·02 ft/sec.²
(Mallock) Unpleasant 5% g.
Constant's Curve Threshold of Unpleasantness.
(1)
(2)
(3)
(4)
(5)
THRESHOLDS OF SENSITIVITY.
(Reiher & Meister)
(1) Just Noticeable.
(2) Easily Noticeable
(3) Troublesome.
(4) Disagreeable (Injurious after a long time).
(5) Dangerous (Injurious after a short time).
Amplitude inches.
Frequency c.p.s.
10⁻²
10⁻³
10⁻⁴
0
10
20
30
40
50
60
70
80
90
100

FIG. 1


(5)
(4)
(3)
(2)
(1)
(1) Just Noticeable.
(2) Easily Noticeable.
(3) Troublesome.
(4) Disagreeable.
(5) Dangerous.
THRESHOLDS OF SENSITIVITY.
(Reiher & Meister.)
10⁻²
4.10⁻³
2.10⁻³
10⁻³
2.10⁻⁴
inches.
AMPLITUDE




ACCELERATION ⟶ ft./sec.²

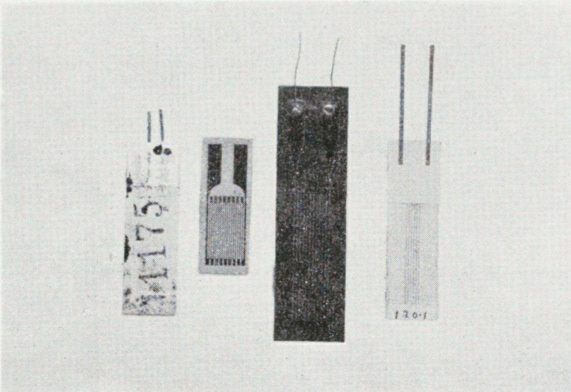



FIG. 3

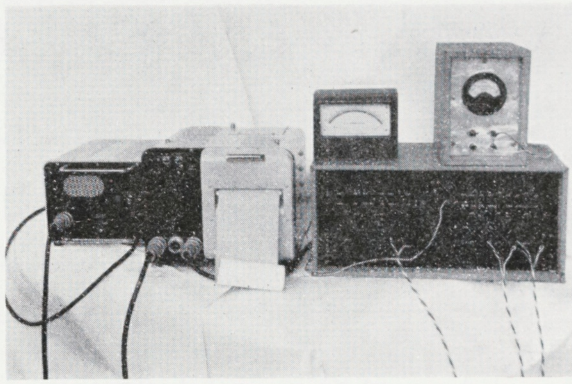


FIG. 4

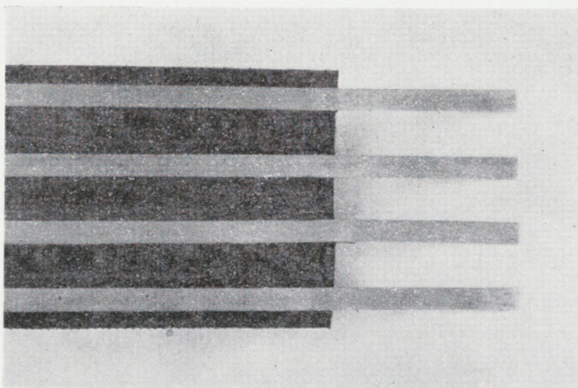


FIG. 5

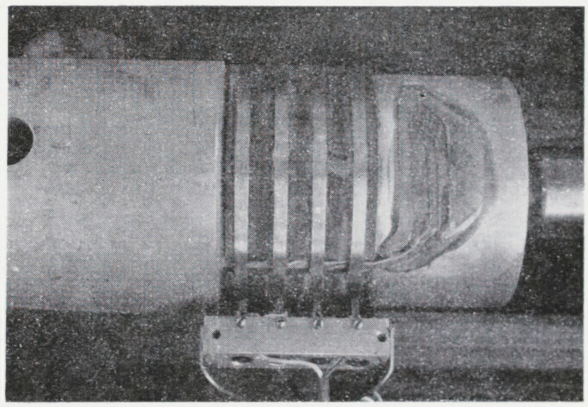


FIG. 6

of the wire or foil grids (either in tension or compression) the electrical resistance of the gauge is increased in the case of a tensile stress or decreased in the case of a compressive stress by a small amount. If the original resistance of the gauge was R ohms and the change in resistance $\delta R$ then it can be shown that $\frac{\delta R}{R}$ is proportional to the mechanical strain, usually described as $\frac{\delta L}{L}$, and is therefore proportional to the mechanical stress within the limit of proportionality of the material. The strain gauges (more than one are generally used) are connected in a "Wheatstone Bridge" configuration which gives an output voltage proportional to the resistance change. The electrical quantities involved are small and are electronically amplified before being recorded directly as a trace on paper. Fig. 4 shows a typical array of apparatus suitable for recording from six sets of strain gauges simultaneously. By the addition of a second six channel amplifier, shown on the right of the photograph, the signals from 12 sets of gauges can be recorded. Time marks and engine revolution marks can also be provided.

Signals from strain gauges on rotating parts are taken off by means of slip rings and brushes. As it is usually necessary to fit slip rings to "endless" shafts the exact diameter of which is not known in advance, a length of rubber insertion is prepared in the laboratory and four parallel strips of brass are bonded along its length. Fig. 5 shows part of one of these strips, which can be made up to 9 ft. 6 in. long. The strips can be cut to length on the ship, wrapped around the shaft and the ends sweated together with a lap joint. Fig. 6 shows the rings connected to a set of gauges suitable for measuring torsional stress. Plunger type brushes of a silver graphite material are used. One pair of brushes and rings supply the gauges with an energising voltage and the other pair take off the electrical signal.

The system has advantages over the Geiger in that a much higher frequency of vibration can be recorded. Traces can be derived from a number of different points simultaneously and a direct calibration can be applied, both before and after vibration records have been taken, in the form of a simulated resistance change in each strain gauge circuit. It will be appreciated that whereas the Geiger Torsiograph measures the amplitude of torsional oscillation and is set up as near a vibration antinode as possible, the strain gauge measures torsional strain directly and is set up as near a nodal point as possible. It is therefore necessary with Geiger readings to refer to the calculated swinging form of the shaft system in order to determine the maximum stresses. The disadvantages of the electrical system are the quantity of equipment needed and the time taken to install it. This time is not excessive however due to improvements in techniques and it is quite possible to fit several sets of gauges in the time it takes a tanker to discharge. The weight of apparatus has also been considerably reduced by the use of transistors.

A final point in favour of the electrical strain gauge system is that records can be taken when the engine revolutions change rapidly; with a Geiger, the seismic mass hits the stops.

## AUTHOR'S REPLY

### To Mr. J. H. Milton

Propeller excitation is usually caused by a combination of insufficient propeller-hull clearance and unsuitable blade form. An unsuitable blade form can give rise to exciting forces even when the clearance is in excess of that usually found to be satisfactory. Methods of improving blade form are discussed on page 8.

The Author believes that vibration is more prevalent in welded than in riveted ships, and also in vessels with engines aft, for the following reasons: —

(1) Generally speaking modern ships contain more welding than old ones, and their machinery is more powerful. Thus the hull damping inherent to riveted construction is reduced, while the probability of generating large exciting forces is increased.

(2) In order to vibrate the hull an exciting force must act at or near an antinode, and since the largest antinode usually occurs at the stern, vessels with reciprocating engines aft are more likely to vibrate excessively than those with engines amidships.

### To Mr. S. Archer

Mr. Archer is correct when he states that changes which are made to reduce one mode of vibration may adversely affect other modes. This must always be borne in mind when altering masses and stiffnesses. As a colleague so aptly remarked: "There is little point in giving a baby a drum to keep him quiet". There have been cases where this has happened but usually the resulting vibration was less harmful than the original. One case the Author remembers concerned changing from a four-bladed propeller to five in order to eliminate hull vibration only to find incipient propeller whirl. Other cases have occurred where engines have been stayed to the hull to prevent engine lateral vibration, and local vibration of masts, accommodation bulkheads and radar equipment has been caused. Such consequent local vibration must be dealt with separately.

The Author finds the example of the six cylinder 4-S.C. auxiliary engines interesting. Weakening the transverse bearers in order to reduce the natural frequency and avoid resonance was the simplest method of eliminating the vibration. No doubt the decision to do so was based on a well-defined, sharply-tuned, resonance curve.

In answer to Mr. Archer's question on the failed bevel pinion for the Voith-Schneider propeller drive, the material was stated to be EN 19 having the following properties:—

| | |
|---|---|
| Dia. of test piece | 0·564 in. |
| Gauge length | 2·0 in. |
| U.T.S. | 49·6 tons (sq. in.) |
| Elongation % | 22·0 |
| Reduction in area % | 56·0 |
| Fracture | Cup and cone 9 silky fibrous |
| Hardness at flame-hardened zone on pinion teeth | 450 V.P.N. |
| Hardness at centre of teeth, roots and below teeth on pinion and wheel | 220/240 V.P.N. |

With regard to Figs. 28A to F, the Author refers Mr. Archer to the reply to Mr. Burton Davies. The Author agrees that constant limits of acceleration are unsatisfactory for assessing permissible hull vibration. It is true that the human body can tolerate increasing acceleration as the frequency rises, but it is also true that it can tolerate more vertical vibration when sitting or lying than when standing, and more horizontal vibration when standing than when lying. Intermittent vibration is more unpleasant than continuous, especially if it stops and starts abruptly. It also appears that the actual activity in which the body is engaged affects its tolerance to vibration. More complaints seem to originate in the smoke rooms and bars of passenger vessels than in the cabins. Bad vibration in a hospital has failed to excite comment, but slight vibration on a navigating bridge will often give rise to complaint. The body can tolerate more vibration when active physically than when active mentally.

The Author agrees that when giving an opinion as to what constitutes unacceptable vibration, consideration must be given to many more factors than frequency and amplitude, but as a general rule the limits given in the Paper will be found to be adequate. To those who require to describe a vibration more fully, the Author would recommend Meister's curves which Mr. Archer includes in his discussion.

### To Mr. J. Burton Davies

The Author agrees with Mr. Burton Davies that in the past 10–15 years the number of vibration cases dealt with each year by the Society has increased. The reasons he suggests for this are probably contributory; another one is that the Society usually solves the problems given to it.

With regard to the frequency charts, Figs. 28 A to F and Fig. 29, these did not require such a large amount of work as would appear. Figs. 28 A to F are identical with the exception of the lines embodying a correction for changes in mean draught. These lines are marked "breadth" on the diagrams. Thus there is actually only one diagram which has been modified six times. It is unfortunate that the size of the diagrams gives them an importance in the paper which was not intended. The Author would have preferred them to have been reduced to a size which would have enabled them to have been accommodated three to a page. It would then have been obvious that they were approximate and to be used only to estimate the probable mode of vibration. However, since they have caused a certain amount of comment, a brief account of how they came to be drawn might not be out of place.

When the Author found that certain vessels did not always vibrate sufficiently in the condition at the time of the investigation to enable the mode of vibration to be established, the idea of having some sort of "hull vibration slide rule" presented itself. Such a rule would indicate quickly which mode was being excited when a Geiger could not measure the profile.

In order to make such a device it was necessary that the formula on which it was based should be as simple as possible and, in order to eliminate "crowding" at one end of the scales the terms in the formula should be as free as possible from indices. Further, the terms should be such that their values could be easily determined by an investigator at sea. Formulae by Todd and Marwood and Prohaska were considered but eventually it was decided that the formula chosen was the most suitable. While deciding on the form the rule should take, a chart was drawn similar to those now given and it was immediately obvious that approximate charts could be used for the time being. That there are more accurate methods of estimating hull frequencies there is no doubt, but they are not always available to the sea-going investigator.

In practice the Author usually works out the frequency from a formula and checks it on the charts.

### To Mr. A. E. Toms

Mr. Toms is correct in pointing out that there is an error in the formula given by Panagopulos in his 1950 paper. It was mentioned by Baker in the discussion and acknowledged by Panagopulos. It should have been emphasised in the Paper.

Twin spring couplings usually work very well; the cause of the trouble was slackness developing through wear. A cure was effected by taking up the slackness between the springs and the gunmetal pads on which they bore.

### To Mr. G. S. Pidd

This contribution is useful since it underlines some of the fundamentals of vibration engineering.

### To Mr. J. S. Shand

Mr. Shand is theoretically correct in stating that, in Figs. 16A, B and C the bending moment diagrams should be modified and a parabola drawn in way of the uniformly distributed load on the stern tube bearing. However, when the Author began slope-boring calculations some

years ago he used both a parabola and a straight line, and since no significant difference was obtained in the final answers, he has continued to use the straight line for the sake of simplicity.

With regard to Figs. 28A to F, the Author refers Mr. Shand to the reply to Mr. Burton Davies.

When changing the mass distribution along a hull, mass is often added without re-distribution of the original mass, but it is rare for the original masses to be simply re-distributed; hence it is difficult to give a satisfactory comment on this matter. In practice, as long as the five points given on page 17 of the Paper are borne in mind it is generally best to adopt the most economical method of mass re-distribution first.

To Mr. J. M. Jennings



The Author thanks Mr. Jennings for his detailed description of the strain gauge technique used by the Society. Less than a week before writing this reply Mr. Jennings and the Author used the equipment successfully to determine vibratory stress in a small gear box.

Mr. Jennings mentions that with a Geiger it is necessary to refer to the calculated swinging form in order to determine the maximum stress when dealing with torsionals in a transmission system. This is also true when using strain gauges unless the gauges are placed at a node; in that case it is necessary to refer to the swinging form in order to locate the node.

Printed by Lloyd's Register of Shipping
at Garrett House
Manor Royal, Crawley, Sussex, England

For Private Circulation amongst the Staff only

# Lloyd's Register Staff Association

Session 1960 - 61

Paper No. 3

# NUCLEAR ENERGY—ITS SOURCE AND ITS APPLICATION TO MARINE ENGINEERING

by

B. HILDREW, M.Sc., D.I.C.

LLOYD'S REGISTER OF SHIPPING

71, Fenchurch Street, LONDON, E.C.3

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# Nuclear Energy— Its Source and Its Application to Marine Engineering

**By B. Hildrew, M.Sc., D.I.C.**

It is, of course, impossible to fulfil the promise contained in the grandiloquent title of this paper and to include a complete description of the basic principles of Nuclear Energy, but it is intended to try and provide a brief survey of the basic facts of matter in so far as they relate to this particular subject, for the benefit of those of my colleagues who may consider life too short to embark on a full study of the subject.

It is common knowledge that matter consists of atoms and that atoms are essentially extremely minute "solar systems" with a nucleus of particles called "neutrons" and "protons" in approximately equal numbers constituting the "sun" and with a number of "electrons" equal to the number of protons in orbit around this nucleus. The protons have a positive electrical charge, the electrons have a negative charge. The chemical properties of a substance are decided by the number of electrons in the uncharged state, i.e., the number of electrons which are matched by protons in the nucleus.

The electrons orbit in "shells" round the nucleus. There are a maximum of two electrons in the innermost shell and a maximum of eight electrons in each of the outer shells. When each shell has its full complement of electrons, the substance formed is an inert gas, i.e., an extremely stable element.

Even when an atom possesses a large number of electrons all in shells orbiting around its nucleus, it is still virtually empty space. The radii of protons, electrons and neutrons are about $10^{-13}$ cm. and the radius of an atom is about $10^{-8}$ cm. These are, of course, very small distances and difficult for most people to comprehend. If we have a goldfish bowl full of water and we magnify it up to the size of the world, an atom of hydrogen or oxygen would look to us about the size of a tennis ball. The word "ball" is, of course, a misnomer as such an atom would consist of a number of minute particles about $10^{-5} \times$ the radius of the tennis ball orbiting around a nucleus of similar dimensions as described above.

If two elements meet and each possesses an outer shell which does not contain its full complement of electrons, they will endeavour to combine and share their electrons in order to complete their shells. This is termed chemical reaction.

Thus it might be said that chemistry is the behaviour pattern of various groups of electrons. It will be noted that chemistry is completely independent of the group of uncharged particles in the nucleus referred to as neutrons. Thus an element might have a varying number of neutrons in its nucleus, this will not change its chemical properties. Additional neutrons will, however, increase the weight of the atom and accordingly it is possible, using complex diffusion techniques, to physically separate chemically common atoms which possess differing numbers of neutrons in the nucleus. The resultant substances are termed the isotopes of the element.

Such isotopes are stable and occur naturally. For lighter elements, the neutron proton ratio in the nucleus is almost unity, but as we move towards the heavier elements a larger proportion of neutrons is required in order to overcome the forces of electrostatic repulsion between the protons. The nature of the forces existing between neutrons and protons is not fully understood and it is necessary to approach the structure of the nucleus empirically.

When an isotope exists with a neutron proton ratio differing from that required in the stable nucleus it is radioactive and it undergoes spontaneous change or "decay" at a definite rate, in such a way as to bring the neutron proton ratio back to stability.

Such isotopes are found in nature as the heavy elements in the atomic table, i.e., thorium and uranium, but most radioactive isotopes are now produced in a nuclear reactor when a nucleus of an atom is fissioned. The decay process can occur in a number of ways. The heavier radioisotopes eject helium nuclei, termed alpha particles. Where an excess of neutrons exist in the nucleus a neutron will be spontaneously converted to a proton and an electron will be ejected—this is termed a beta particle. Where an excess of protons exist in the nucleus a positively charged electron will be ejected and effectively a proton is converted to a neutron—this also constitutes beta radiation.

Another effect which can be observed wherever the nucleus is in an excited state, i.e., whenever it is unstable, is the emission of a gamma ray. This is one way the nucleus disposes of excess energy, and such a phenomenon often accompanies alpha and beta radiation.

There are other possible modes of decay which can occur, but the above summarizes those commonly met in a reactor.

The decay of a radioisotope is expressed in the terms of its half life, i.e., the time required for one half of the atoms originally present to decay. The half lives of the various radioisotopes range from a fraction of a second to millions of years.

Thus as a result of a nuclear reaction radioactive isotopes are produced. Such isotopes decay and in the process of so doing may emit alpha, beta and gamma radiation.

**The Basic Concept of a Nuclear Reactor**

Chemical reaction between materials involves a rearrangement of the electrons. Nuclear reactors are associated with the neutrons and protons in the nucleus of the atom.

Einstein in 1905 developed his special theory of relativity which indicated that mass and energy were related and that energy (in ergs) was equivalent to mass (in grams) multiplied by the square of the velocity of light (cm./sec.).

It is this source of energy which is tapped in a nuclear reaction.

The square of the velocity of light is an extremely large number and its size explains why the equivalence of mass and energy is not observed in ordinary chemical reactions. When 1 lb. of coal is burnt, the energy released represents a change in mass of the order of one ten millionth ($10^{-7}$) of a pound and this, not unnaturally, passes unnoticed. However, gamma rays given off by radioisotopes can have high energies and it is possible to determine the mass equivalence of such energy experimentally by the technique of mass spectrometry.

Einstein's theory remained just a theory until the year 1932 in Cambridge, when it was shown that if certain light elements, e.g., berrylium, are bombarded with alpha particles, radiation is emitted which consists of neutrons. Thus for the first time the physicist had a supply of neutrons, and he could now bombard elements with neutrons. The elements chosen for bombardment were those at the heavy end of the periodic table as it was hoped to add neutrons to the nucleus and produce new elements heavier even than uranium. However, it was discovered that the bombardment of uranium by neutrons produced a split or fission of the heavy nucleus into two radioactive fragments accompanied by the release of a large amount of energy. Later work found that a number of elements including the common isotope of Uranium 238 (the "238" is used to specify that uranium isotope the sum of whose neutrons and protons is equal to 238, i.e., 92 protons, 146 neutrons) could be fissioned by fast neutrons, but the rare isotope Uranium 235 (92 protons and 143 neutrons), present in natural uranium as 0·7 per cent, could be fissioned by relatively slow neutrons called thermal neutrons. Further research showed that Uranium 235 was the only naturally occurring isotope which could be fissioned by thermal neutrons.

Neutrons possess no electric charge and consequently they can approach the nucleus of an atom without experiencing any electrical repulsion, therefore they need very little kinetic energy to approach and react with the nucleus.

However, when produced in a free state, most neutrons are moving at very high speeds, about one-tenth the velocity of light, these are termed fast neutrons.

As they go through matter they collide with the atomic nuclei and a transfer of energy takes place. The neutrons are slowed down by such collisions until the average kinetic energy of the particle is of the same order as that of the nuclei. Such neutrons which have had their energy moderated in this manner are termed thermal neutrons. Thermal neutrons have a velocity of about one mile per second.

Slow or thermal neutrons are of great importance as they have a much greater chance of interacting with a nucleus. The quantum theory propounds that though energy can be transmitted both through movement of a particle and by wave motion, these two modes of transfer cannot be accurately separated, waves behave as particles and particles can exhibit wave-like properties. Further, the wavelength of any particle is inversely proportional to its kinetic energy, thus the slower a particle moves, the greater its wavelength and the greater its effective diameter. Thus as the neutron is slowed down, its effective diameter gets larger and the probability of interaction with an atomic nuclei is increased.

Another way of looking at the problem is the logical one that if a neutron is passing through atoms and has a low velocity it spends more time in the vicinity of any atomic nuclei it might be passing and thus the chances of its being caught are greater.

For elements other than uranium the neutron does not fission the nucleus but might be captured by it. This upsets the neutron proton ratio of the element and, in consequence, the nucleus is in an excited state. The excess energy is disposed of by emission of a gamma ray. The resultant product is an isotope of the original element and may or may not be radioactive. If it is radioactive it will decay probably emitting beta radiation as described earlier.

Once the physicist learnt that fission was possible using an isotope of uranium, considerable effort was concentrated on an examination of the phenomenon. It was found that when the nucleus of the uranium atom fissioned, it could split in a number of ways and in each case a balance sheet of the masses of all substances present before and after fission could be determined by use of the mass spectograph. This balance sheet revealed that the mass of the fission fragments was always less than the mass of the original nucleus plus the neutron which caused the fission. The missing mass had been converted into energy, according to Einstein's mass-energy relationship.

In fact, all the energy released ultimately appears as heat energy and the major part, about 80 per cent, is immediately available in the kinetic energy of the fission fragments. The amount of energy produced by fissioning one gram of Uranium 235 is approximately one megawatt day. Thus the fissioning of one ton of uranium is equivalent to burning over 2½ million tons of coal.

As already indicated, uranium is a heavy element with a high neutron proton ratio in its nucleus. When the nucleus is fissioned the fragments consist of a number of random elements of roughly half the atomic wt and these elements can only be stable if the neutron proton ratio approaches more nearly to unity. Accordingly, though the nucleus can split in many different ways the resultant fragments are excited and unstable. They become stable by ejecting neutrons or by converting the excess neutrons to protons and emitting beta radiation.

Thus a self-sustaining source of neutrons is available providing it is ensured that at least one neutron from each fission can, in turn, fission another nucleus. This is not easy as capture of a neutron in the nucleus is possible and there are a number of other nuclear processes which absorb neutrons.

Obviously, if the amount of Uranium 235 present is increased, the chances of a neutron fissioning the Uranium 235 are increased. Hence expensive isotope separation plants have been built to achieve a fuel enriched in the Uranium 235 isotope.

Again, if the ejected fast neutrons could be slowed down efficiently to become slow neutrons the chance of nuclear reaction increases. Thus by siting discrete pieces of uranium in a medium capable of slowing down or moderating the speed of the neutrons the probability of fission increases. The resultant pile of materials is a nuclear reactor.

When the fast lightweight neutron hits a heavyweight nucleus it sinks into it and is captured. A neutron of lower kinetic energy is expelled and the nucleus, because it has absorbed energy is excited. It will return to its ground stability emitting gamma radiation. If the neutron hits a nucleus of light weight, it collides and shares its energy, rebounding at a reduced speed, dependent on angle of impact, much the same way as in snooker the white ball collides with the others. Uranium cannot be used as a moderator, nor can it be mixed homogeneously with the moderator, as the Uranium 238 isotope will probably capture the fast neutrons before they can be slowed down. Uranium fuel must be made in discrete packets, using fuel rods which must be physically separated from each other and the distance or lattice between the fuel rods is dependent upon the ability of the moderator chosen to slow down the neutron from fast to thermal velocity at which speed it is best suited to meet and fission a Uranium 235 atom.

The nuclear heat produced by fission must be transferred from the site of the reaction, i.e., the fuel rod. Accordingly, a coolant must be provided. The choice of coolant is limited to those fluids possessing lightweight nuclei. In addition, such nuclei must not absorb neutrons. As the same properties are required from both moderator and coolant, it is often possible to use a common liquid for moderator and coolant.

**How a Reactor can be Controlled**

Care must be taken that any material capable of absorbing neutrons is, as far as possible, eliminated from the reactor unless the deliberate movement of such material can be used to control the supply of neutrons and consequently the supply of heat.

Neutrons will be lost by escape from the outer surface of the reactor, but as such escape will be proportional to the surface area whilst the production of neutrons is proportional to the volume it can be seen that, relatively, the larger the volume the smaller the number of neutrons which escape. It is possible, of course, and economic, to scatter the escaping neutron back into the core by surrounding the core with a neutron reflector.

When the chain reaction is just sustained the system is said to go critical, i.e., the neutrons have a multiplication factor of one. To produce power requires that the multiplication factor of the neutrons should be capable of exceeding unity as this is the only way of increasing the number of neutrons and hence the fission rate up to any desired level. Thus the reactor must be made greater than its critical size and the multiplication of neutrons must be controlled by the movement of neutron absorbing material, i.e., control rods. The control rods are pulled out of the core until the reactor is just critical, at such a point no power is produced. On pulling the control rods out further the chain reaction is permitted to diverge and a rise in power results. When the desired power level is reached the effective neutron multiplication factor must be reduced to unity by rod insertion, when the required power will be sustained. If this is not done the chain reaction will continue until the core distorts and melts under high temperature. If the control rods are inserted further into the core the multiplication factor falls below unity and the chain reaction dies.

As described earlier, one of the effects of fission is to produce random radioactive isotopes as well as neutrons. These isotopes are absorbers or poisons and will capture neutrons and emit more radiation. This is a further reason why a reactor must be made greater than its critical size. The excess reactivity built into the core and held down by the control rods is a measure of the life of the core.

The escape of neutrons from the fissioned nucleus is not always instantaneous. The majority of neutrons are released instantaneously, these are termed prompt neutrons. Obviously if such neutrons are produced in sufficient quantity when the control rods are withdrawn, the power level will rise instantaneously and it may not be possible to reinsert the control rods before damage is done to the reactor. However, a small minority of neutrons are produced after radioactive decay of a number of the fission products and such neutrons are termed delayed neutrons. If we limit the withdrawal of the control rod to ensure that the multiplication factor can never exceed the percentage of delayed neutrons released, we will

always have time to reinsert control and shut down if we so desire.

**Materials Used in Reactor Construction**

Let us now look at the materials available to construct a reactor, bearing in mind that our choice is controlled by the factors referred to above. Uranium can be in its natural state, i.e., containing 0·7 per cent Uranium 235, or it can be enriched at considerable expense up to 90 per cent or more. Such high enrichment results in small reactor cores and has military value, but economically it is not attractive, at the moment, to enrich above about 4 per cent Uranium 235.

Other fuels can be produced, as described below, but they are not developed to the point where installation in a power reactor is proposed.

When slow or thermal neutrons are subject to capture in materials other than Uranium 235, such neutrons are lost in so far as the nuclear chain reaction is concerned. Atoms of Uranium 238, the major isotope of uranium, will capture some of the escaping neutrons and in the process be converted to Uranium 239. This isotope of uranium is, of course, radioactive and decays by changing one of the neutrons in the nuclei to a proton and emitting a beta radiation. The new artificial element so formed has been named Neptunium. Neptunium in turn decays to form another artificial element called Plutonium. Plutonium is relatively stable and can be chemically separated from the uranium fuel. When struck by a thermal neutron it will fission in a manner similar to Uranium 235.

It has also been found that Thorium 232 will capture a neutron and after radioactive decay another relatively stable isotope of uranium, Uranium 233, is produced. Uranium 233 will also fission when struck by a thermal neutron.

Thorium 232 and Uranium 238 are called fertile materials. Obviously if the number of neutrons resulting from fissioning of either Uranium 235, Uranium 233 or Plutonium can be utilised to maintain a chain reaction and, in addition, it is arranged that some of the surplus neutrons are captured by Thorium 232 or Uranium 238, it is possible to make fuel as your reactor produces heat. If the neutron economy is such that more fuel is made than is fissioned, the reactor is breeding fuel. The ultimate purpose of the fast reactor contained in the large sphere built to the Society's requirements at Dounreay, is to burn plutonium for power production and to breed enough fuel from a thorium or uranium blanket round the core to replace the burnt fuel. More neutrons can be obtained from each fissioned atom if the neutron doing the splitting is a fast neutron. Accordingly, the Dounreay Experimental Reactor is a fast reactor and as it is a fast reactor the fuel is, of necessity, enriched.

Moderators, as already stated, must consist of light nuclei and must not absorb thermal neutrons. Graphite, beryllium (at present an expensive element to obtain and a toxic one to work with) and heavy water (an isotope of water which can only be separated from ordinary water at great expense) are the only materials capable of moderating a natural uranium reactor. Ordinary water, or light water as it is generally referred to in the context of nuclear reactors, has a higher absorption cross-section and therefore captures too many neutrons. However, if the fuel is slightly enriched, thus increasing the number of neutrons available, it is possible to use water as a moderator.

In a highly enriched fast reactor no moderator is required as the fast neutrons are used to fission the Uranium 235 nuclei.

Oil consists of a complex of elements, but it is hydrogenous, i.e., contains a lot of light atoms and but for impurities it might well be used as a moderator. A by-product of the oil industry known as terphenyl, can be produced relatively free from impurity and this organic liquid can be used as a moderator.

When the moderator is liquid it is possible to use it to carry the heat away from the fuel, i.e., to use it as a coolant.

The nuclear requirements of a coolant are similar to the moderator, i.e., low neutron capture cross-section, and the ideal coolant would be hydrogen or helium. $CO_2$ is, of course, the cheapest and most common gas to be used. Heavy water and light water can also be used. In a fast reactor there is no requirement for a moderator. Such reactors have very small, highly enriched cores and the major problem is to remove a lot of heat from a very small volume. Liquid sodium is a material well suited for this task.

**Reactor Types**

There are obviously a number of combinations of these reactor materials, each of which is capable of making a reactor.

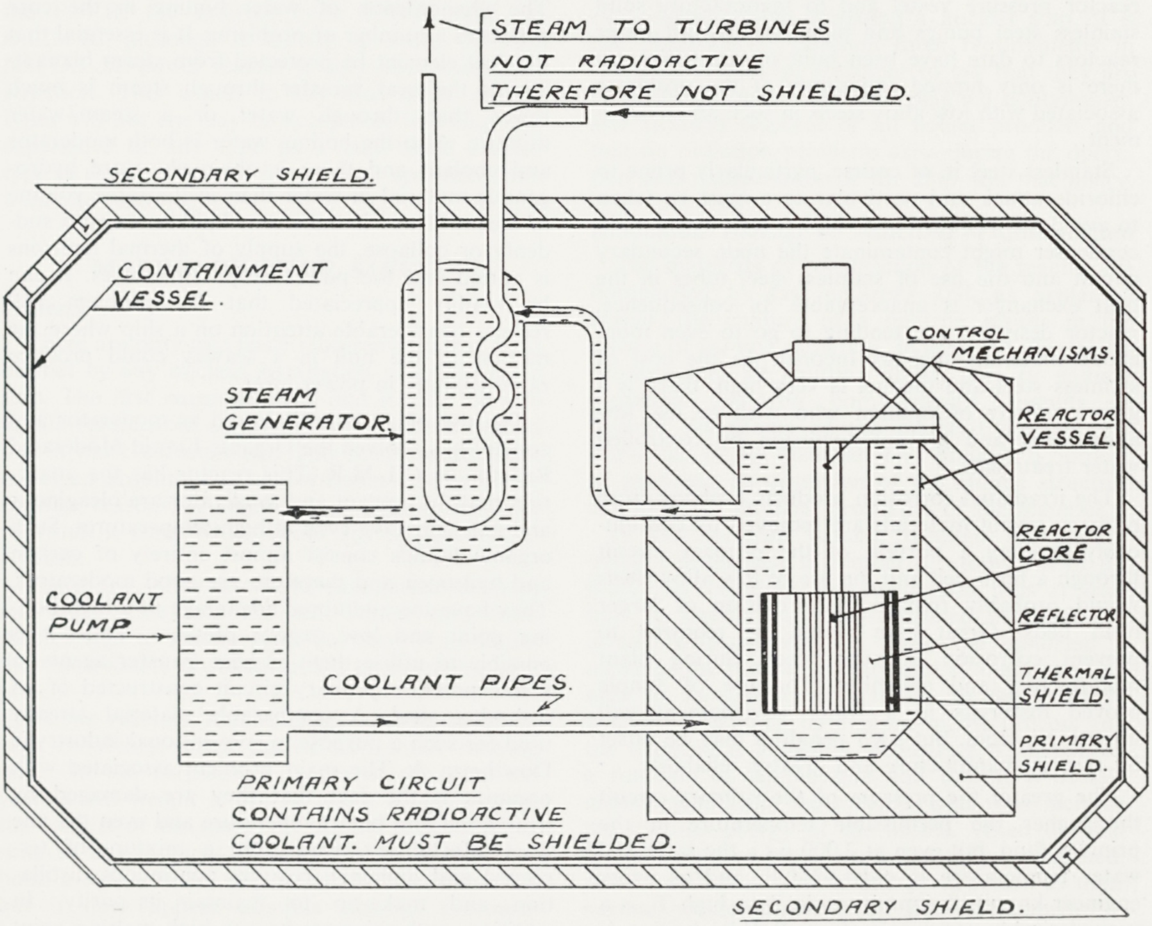
The hazards connected with such reactors are the resulting fission products. The fissioning of the uranium atom can produce up to two hundred different compounds with radioactive half lives which range from fractions of a second to hundreds of years. The human body does not take kindly to alpha, beta or gamma radiations and neither does it like neutrons bombarding it. It is thus necessary to ensure that under no circumstances shall any person be subject to anything but extremely limited irradiation and that the ingestion and inhalation hazard be completely eliminated. This is achieved by ensuring that the plant is adequately shielded and that the fission products are contained as far as possible in the fuel rod. This is not easy as the fissioning of the uranium nuclei with the associated heating can produce distortion of the fuel rod. It is common practice to seal the fuel rod into a can and thus prevent the escape of fission products. The canned fuel element has its can carefully designed and fitted to ensure its integrity and the coolant which removes the heat from the can must also be continuously examined to ensure it is not deteriorating under irradiation. The fuel elements in their

cans are grouped into a support structure which forms the matrix of the reactor core and its moderator. This core structure is supported inside a pressure vessel. The neutron-absorbing control rods are inserted in the core structure prior to assembly of the fuel elements and these control rods are operated through mechanisms located outside the reactor vessel. The heat carried away by the coolant, which is either pumped round the primary circuit or circulated by natural convection, is used in a heat exchanger to generate steam which can, of course, be used in conventional turbines. Thus the reactor with its associated shielding, pumps and heat exchangers replaces the boiler and fuel of a conventional turbine ship (Fig. 1).

It is proposed to discuss only those reactor systems which are already developed sufficiently ashore to indicate the feasibility of their installation in a hull. We are thus reduced to reactors using uranium as a fuel and graphite or hydrogenous materials, i.e., light water or organic liquids as a moderator and gas or again light water, heavy water or organic liquid as a coolant. Britain has all her experience in gas cooled reactors of the Calder Hall type which are graphite moderated and cooled by $CO_2$. This reactor type is being developed through the Advanced Gas Cooled Reactor using $CO_2$ coolant to DRAGON, the high temperature gas cooled reactor, using helium as a coolant.

Gases have poor heat transfer characteristics compared with liquids and require high pumping power. At high temperatures and pressures a considerable leakage can occur. All our gas cooled reactors to date have been graphite moderated and as temperatures increase the exclusion of oxygen from the coolant is of major importance, as oxidation of the graphite can be rapid and dangerous. Although potentially it is possible to achieve a small gas cooled core by using a degree of Uranium 235 enrichment in the fuel and dispersing the fuel in graphite cans in the graphite moderator, such reactors are only on paper at the moment and the marinisation of the Advanced Gas Cooled Reactor, the most recent development from the Calder Hall Reactor, which is at present under construction in Britain, results in an unacceptably large reactor for installation in a hull.

Heavy water when used in a reactor adds considerably to the cost. Further, the care required to conserve such an expensive fluid involves the designer in even greater expense. Light water, however, is plentiful and cheap and the possibility




Outline sketch of a Reactor Installation

FIG. 1

of moderating and cooling a reactor core with such a fluid is extremely attractive. The heat transfer characteristics are good and considerable experience exists in utilising water as a heat transfer medium. Such a reactor is called a pressurised water reactor or P.W.R.

Both heavy water and light water are subject to radiation damage when used as coolant and/or moderator, and consequent decomposition into hydrogen and oxygen occurs. The release of radioactive gases to atmosphere is strictly limited by law and accordingly, it is usual to synthesise the oxygen and hydrogen back into water and re-inject it into the system.

The possibility of corrosion occurring in the reactor circuit cannot be countenanced. Corrosion can be a major problem in a water reactor especially if the oxide film becomes detached and after irradiation during passage through the core collects in pockets in the circuit and produces unacceptably high local radiation. In addition the flow channels through the fuel elements might choke with the corrosion products and the local hot spots so produced would damage the fuel element can.

It has been American practice to limit corrosion by using stainless steel as a clad material in the reactor pressure vessel and to manufacture solid stainless steel pumps and pipes. Almost all water reactors to date have been built by the U.S.A. so there is only limited experience of the problems associated with low alloy steels in such an environment.

Stainless steel is, of course, particularly prone to chloride attack and particular care must be taken to avoid this problem in a ship. A leak in the main condenser might contaminate the main secondary circuit and the use of stainless steel tubes in the heat exchanger is unacceptable. In consequence, reactor designers are tending to go to even more exotic materials such as Inconel. As the cost of stainless steel and inconel is very high, there is a growing body of opinion who wish to use low alloy steels and prevent corrosion by controlled water treatment.

The irradiated corrosion products evolving from primary circuit materials are removed by continuously flushing a portion of the primary circuit through a resin bed and the use of low alloy steels would probably require the provision of larger resin beds. Great care would be required to prevent corrosion of such steels during plant manufacture and assembly. The use of simple proved materials in a water environment will impose penalties, but such penalties may be offset by ease in manufacture and greater reliability.

The greater the pressure of the primary circuit the higher the permissible temperature in the primary fluid, but even at 2,000 p.s.i. the saturated water temperature is only 636° F. and as every engineer knows, thermodynamically a high $T_1$ is a very desirable parameter. In a P.W.R. boiling is not permitted and accordingly the operating temperature is maintained below the saturated steam temperature. Thus at 2,000 p.s.i. the primary circuit water temperature might only be 500° F.

All water and organic liquid cooled reactors suffer from this defect and consequently steam conditions obtaining in the secondary circuit are poor by modern standards.

It is only in the gas cooled reactor concept that the future possible development of materials will lead to a high primary circuit temperature and consequently to steam temperatures more suitable to present day turbine machinery.

Thus the pressurised water reactor concept necessitates high pressures with consequent design and manufacturing problems of the primary circuit.

However, it is obvious that a lower primary circuit pressure and hence smaller primary circuit scantlings would be obtained if sub-cooling was eliminated and boiling was permitted in the core. Such a reactor is termed a boiling water reactor or B.W.R. The steam from the core could be passed directly through the main turbines, but the possibility of a gradual build-up of radioactivity in the main engines discourages the development of such a design for ship use at this stage and a secondary steam circuit is at present preferred. The phenomenon of water boiling in the core produces a number of problems. It is essential that the fuel element be protected from steam blanketing as the heat transfer through steam is much lower than through water or a steam/water mixture. Also the boiling water is both moderator and coolant and there is obviously more hydrogenous material in water than in the same volume of steam. Thus, if the steam bubbles expand suddenly or collapse, the supply of thermal neutrons is varied and the power output fluctuates. It can be readily appreciated that the problem will require considerable attention on a ship where the motion of the hull in a seaway could produce rapid changes in power level.

The use of an organic liquid as moderator and coolant has evolved the Organic Liquid Moderated Reactor or O.L.M.R. This reactor has the attraction that the coolant and moderator are oleaginous and non-corrosive even at high temperatures. Such organic liquids consist almost entirely of carbon and hydrogen and therefore are good moderators. They have the additional advantage of a high boiling point and low vapour pressure. Thus, it is possible to utilise them as heat transfer agents in a low pressure primary circuit constructed of an orthodox steel. A comparable material already used for such a purpose in conventional industry is Dowtherm A. The main problem associated with organics is the fact that they are damaged by irradiation and high temperature and even the one least affected by irradiation, a mixture of terphenyl and diphenyl, requires continuous distillation and make-up to maintain its purity. In addition, such mixtures have a high melting point (280° F.) and thus trace heating of the primary circuit is necessary.

However, once the marine engineer accepts the concept that water and steam are not the only heat transfer mediums in the world, this reactor has many attractions, as the engineering know-how required to build the component parts is well within the scope of industry and the fact that the working fluid is non-corrosive, permits orthodox materials to be used in the pressure circuit.

The use of a liquid metal as a coolant is very attractive as it has excellent heat transfer characteristics. The materials best suited to this technique are sodium or a sodium potassium eutectic. Unfortunately such materials react violently with water and deteriorate in the presence of even minute quantities of oxygen. An additional disadvantage is that irradiation produces an active isotope with a long half life and high induced radioactivity occurs. Maintenance work on the reactor is consequently extremely difficult. These problems would obviously defeat it in the context of a marine reactor although it is worthy of note that America fitted such a reactor into the submarine "Seawolf". After apparently satisfactory operational experience it was decided to replace it with a P.W.R.

Thus we see that at this moment in time there are three reactor types operating ashore which would appear to be adequate in a ship. These are the P.W.R. the indirect cycle B.W.R. and the O.L.M.R., although it should be noted that the first O.L.M. power reactor is only now under construction. This is not to say that other reactor types will not one day be acceptable in a ship, but experience of any type as a land-based reactor type is essential before it could be operated from a mobile platform.

## MARINE REACTOR SAFETY

### General

There are only two basic requirements that must be met by any nuclear installation proposed for a ship. The first requirement is that it must be safe in all foreseeable circumstances and the second that it must be economic. This latter requirement is not an absolute one as, for defence purposes or prestige reasons, it might be considered desirable to install a plant which could not be operated at a profit.

There are safety problems associated with size and integration into the hull which vary from reactor type to reactor type, but there is no doubt that most safety problems could be overcome at a price.

Mobile reactors require small specific volumes, high reliability, small capital and small running costs. In the foreseeable future of the next ten years small weight is not of major importance in the context of the merchant ship. It is accurate to state at this moment in time it is not possible to build a safe nuclear ship which will be economic, but it does appear possible that in the near future large nuclear ships might be able to meet the safety requirements and yet reach economic parity with conventional ships.

In general the safety requirements afloat are only slightly more stringent than those for land-based plant. There are four major differences between a ship-based and shore-based reactor:—

(1) The operators on the ship live with the reactor 24 hours a day.

(2) The ship operates between large centres of population and therefore any hazard is brought in close proximity to a large number of people.

(3) The platform supporting the reactor moves.

(4) The possibility of an accident external to the reactor, e.g., collision, grounding, etc., is introduced.

Items 1 and 2 above draw attention to the requirements for adequate shielding of personnel from the fission product activity. Item 3 requires a study to be made on the stability of any proposed reactor when subject to ship movement. Item 4 introduces a number of problems. As an example, it is necessary to design the components of the reactor system to withstand the worst foreseeable shock load. It is also necessary to build into the hull protection against collision and grounding in way of the reactor.

The Society has published a number of provisional requirements to guide both engineers and naval architects in designing a nuclear ship. It is not proposed to examine these requirements in detail. It is perhaps sufficient to say that they are designed to ensure both the planned containment and planned disposal of all fission products and that no radiation problems arise during the operation and maintenance of the ship and machinery.

### Irradiation Damage to Materials of Construction

The materials of construction of the reactor are bombarded by fast neutrons and, as explained earlier, the capture of a neutron results in the release of gamma radiation. In addition, the fission products are all emitting alpha, beta or gamma radiation. Neutron bombardment disrupts or distorts the atoms of the material and of any impurities in the material. This presents a number of problems as distortion of the atomic structure can alter the physical properties of the material.

A fast neutron passing through the reactor vessel will displace a number of atoms out of the lattice by colliding with them and thus at least half its energy may be dissipated in producing atomic displacements. A lattice so distorted is unstable thermodynamically and if the atoms are able to move they will return to their normal position. Heat will be evolved in the process and the material is annealed. Annealing is, of course, a function of temperature and thus it is usually necessary to heat the material and thus increase the thermal energy of the atoms. When the displaced atom, or recoil atoms as they are termed, possess sufficient thermal energy to return to their normal position they do so, and the temperature at which this occurs is termed the annealing temperature. The stored energy in the atom is then released and the material will experience a rapid

rise of temperature. The amount of stored energy released is a measure of the irradiation damage. Thus in low temperature graphite moderated reactors it has been necessary to anneal the graphite by heating, when such stored energy is released as additional heat. It was during such a procedure that the Windscale accident occurred.

For any material the radiation damage is a product of the intensity of the radiation multiplied by the time of exposure. Radiation damage to metals is almost entirely due to fast neutrons and the effect of such bombardment on a metal is to increase its hardness and its shear strength and decrease the ductility. Thus steels under irradiation become more brittle and as reactor pressure vessels and pressure circuits are held below the anneal temperature, care must be taken to choose a steel which can be subjected to fast neutron bombardment throughout the projected life of the ship without unacceptable deterioration. All steels proposed for reactor vessels are now being tested in high flux research reactors to ensure that they will meet this requirement and, in addition, test coupons are included in the reactor vessel itself and withdrawn periodically throughout the reactor life. Only steel in the immediate vicinity of the core is subject to sufficient neutron bombardment to affect its physical properties and the major item of plant affected is the reactor pressure vessel.

Impurities in the steel also require careful assessment before acceptance of the material. As an example, cobalt can only be tolerated in minute quantities as the cobalt atom will absorb a neutron and become radioactive. Radioactive cobalt has a half life of over five years and decays emitting both beta and gamma radiation. This isotope is, of course, used in the cobalt bomb for gamma radiography. The presence of cobalt in a steel used for a reactor part makes even limited access for inspection or repair of that part impossible.

**Shielding**

In order to prevent irradiation of personnel it is necessary to shield the reactor. On land this is achieved as cheaply as possible by surrounding the reactor vessel with a large amount of concrete.

Concrete is not easily assimilated into a flexing structure and accordingly, other materials more suited to ship installation must be considered. The purpose of the shield is to attenuate beta and gamma radiation and to trap fast neutrons escaping from the core. Obviously the closer the shield can be to the reactor vessel the smaller it will be, and the greater the protection to personnel if access to the pumps and other equipment in the compartment is required. When the reactor is operating the radioactive decay of the fission products is, of course, a maximum and it is not possible to enter the space containing the reactor. After shut-down the short-lived products rapidly decay and the level of activity drops sufficiently for personnel to enter the space and carry out maintenance. The primary shield has to be capable of stopping both neutrons and gamma radiation and accordingly it must consist of both hydrogenous material and elements of high mass number, e.g., iron or lead. Thus the neutrons can be slowed down in water and iron and eventually captured by the shield materials. Unfortunately, the capture of a neutron by iron produces a high energy gamma ray which must be absorbed. Shielding design is an inexact science at the moment but the type of primary shield evolving for a ship consists of concentric cylinders of iron contained in an annular shield tank filled with water. To mop up the gamma rays resulting from neutrons captured in the iron an additional absorber is required; this may be achieved by adding boron to the shield water or to the iron. The energy released by the capture of gamma rays and neutrons appears as heat in the primary shield and it may be necessary to make provision to cool the shield.

**The Concept of a Major Accident**

It is obvious that no experience can be obtained in operating a reactor until one is built and in such circumstances it is necessary to examine thoroughly all possible events which might influence the operation of the plant and all possible accidents which might occur. It is, of course, difficult to reach general agreement on what is possible and what is impossible, but ultimately a major accident of sufficient severity must be agreed as being the worst that can possibly be foreseen. This arbitrary accident usually takes the form of complete failure of the primary circuit and rapid consequent failure of a portion of the secondary circuit. An examination of the design might then reveal that as a consequence of loss of coolant, the fuel elements would melt and the molten fuel and canning material might react chemically with water or steam and release chemical energy as well as all, or a proportion of, the fission products contained in the fuel.

The escape to atmosphere of even a small percentage of the accumulated fission products contained in the fuel elements can be so toxic that vast areas of land might have to be evacuated for periods of time measured in years.

Accordingly, having posed the major accident, provision must be made to contain its consequences in the ship. Calculations rapidly reveal that the hull structure in way of the reactor plant cannot be strengthened adequately to contain the pressure rise consequent upon the release of water and steam. Thus a pressure vessel must be constructed around the reactor installation. This containment vessel must possess adequate openings to refuel and maintain equipment and must be integrated into the hull of the ship. Access into this containment vessel will not be possible when the reactor is on load.

It will be a large vessel and the major part will be built while the ship is on the ways. The greatest complication of this, as far as the Society is concerned, is that pressure vessels are going to be

constructed in shipyards, and the standard of workmanship demanded is going to involve the local surveyors in some very tense arguments.

Although the accident to which the containment vessel is designed is arbitrary and extremely pessimistic it is necessary, having assumed that such an accident can happen, to shield the containment vessel or the ship compartment in which it is installed in order to protect crew and, in the event of the accident occurring in port, dockside personnel. The majority of escaping neutrons will have been stopped and core disruption or melt out will have resulted in loss of criticality, i.e., no new neutrons will be produced by the materials and equipment in the containment vessel, but the escaped fission products will be emitting beta and gamma radiation which must be captured by this secondary shield. Thus such a shield must be made of steel or lead. Which material is chosen is an economic problem. The closer the shield is to the containment vessel the smaller it will be in terms of weight and cost. In addition the space in the reactor compartment external to the containment vessel can then be used for ancillary equipment and limited access is desirable to carry out running maintenance on such equipment.

Engine-room watchkeepers spend 8 hours a day adjacent to the reactor compartment and it is usually necessary to shield the after reactor compartment bulkhead and thus permit continuous running of the engine room under all foreseeable conditions, and even to permit limited access after a major accident has occurred in the containment vessel.

**Decay Heat and Reactor Poisons**

As already stated, all the energy available when an atom is fissioned ultimately appears as heat. The greater part appears instantaneously, but about 20 per cent appears gradually as the radioactive fission fragments decay. This delayed release of heat is called "decay heat" and after a reactor is shut-down, provision must be made to remove such heat from the core at a gradually decreasing rate until the radioactive materials in the fuel elements have completely decayed. In power reactors this takes a very long time and it is certain that the reactor will always be required on load again before all the fission products have decayed. In the event of any accident or defect which requires the reactor to be shut-down it must permit sufficient circulation of coolant to prevent damage to the fuel elements, due to overheating. There are a number of methods of removing decay heat depending upon the reactor and its design, but at least one method proposed for any reactor must work up to lists of 50° and must be independent of the normal power supply.

The radioactive fission fragments are, in effect, poison in the core as they absorb neutrons and, accordingly, it is necessary to make the core even larger than strictly necessary to maintain power in order that a surplus of reactivity is available to override these poisons.

Further, some poisons with large absorption cross-sections and fairly long half lives are daughter products of the original fission fragments. After reactor shut-down, neutrons are not available to remove these poisons and the quantity present builds up as the fission products decay. Ultimately the poison itself will decay, but if it is required to restart the reactor before the poison decays, a greater investment of fuel will be required to permit overriding the temporary increase in poisoning. Xenon 135 is a poison which behaves in this manner and accordingly the reactor designer must decide whether to accept that after shut-down he must wait for the Xenon 135 to decay before he can start again or whether he wants complete flexibility, in which case he can arrange either to invest an excess of fuel in the core or to maintain the reactor power output at all times. Continuous full-power operation of the reactor is, of course, possible. The steam generated in the secondary circuit is dumped into an atmospheric condenser when not required at the main turbines. A dump condenser is also of value in the event of a machinery failure or when manœuvring as the reactor is not as flexible a heat source as an orthodox boiler.

**Defuelling and Waste Disposal**

One of the major problems associated with a ship is that of removing the irradiated fuel elements from the reactor vessel to storage and ultimately to a fuel treatment plant ashore.

The frequency of this operation is a matter of economics. If the shipowner had enough money it would be possible to design a core which contained enough fuel for 20 years and thus the core would last out the ship's life. This is, of course, possible in the future if and when fuel becomes cheaper, but at the moment it is usual to plan on a one-, two- or three-year life. At the end of core life the fuel elements, each of which contain enough fission products to cause a major calamity, must be removed and transported to a safe place. It is necessary to open up the ship's hull, containment vessel and the reactor pressure vessel to reach the fuel element and even though the circuit is depressurised and relatively cold, it is desirable to always maintain a single skin of containment around the fuel element. This is achieved by transferring the fuel element in a container suitably shielded to protect personnel and often water cooled to remove the decay heat still being released from the element. The major problem concerned with defuelling is one of logistics. The transfer of each fuel element from the core into its container and the transfer of the loaded container from inside the containment vessel to storage ashore requires considerable cranage. The loaded fuel element container may weigh up to 50 tons and it may be necessary to move 100 fuel elements in this manner. The total time which can economically be allowed for refuelling is 14 days from sail in to sail out.

Whether defuelling should be done at a remote place or in a shipyard must be considered. The

hazard at the shipyard is the risk that in the event of an accident a large proportion of the population may have to be evacuated. The hazard at a remote spot is the problem of transporting the containers across populated country to the reprocessing plant.

In addition to defuelling the reactor periodically it is necessary to remove the radioactive waste products continuously being produced as a result of circuit corrosion and breakdown of moderator and coolant. A continuous bleed off the primary circuit is passed through a resin bed to remove radioactive corrosion products (usually termed "crud") and a degasifier removes and stores radioactive gases. In addition, a certain amount of active liquid waste will accumulate due to leakages, circuit testing, etc.

Arrangements must be made to permit containment of all active waste in the hull and ultimately to discharge it ashore. Indiscriminate dumping at sea cannot be permitted due to possible contamination of fishing grounds or foreshores.

**The Control of Primary Coolant Pressure**

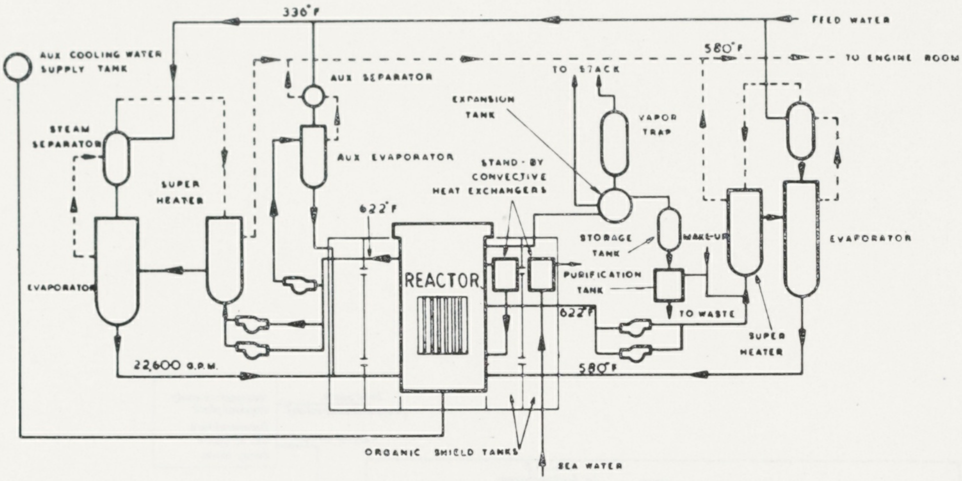
In an orthodox boiler the steam and water pressure and temperature varies slightly with the steam demand. The variations in temperature alter the specific volume of the water slightly but the steam bubble absorbs this change in water volume. In a complete water circuit under pressure a change of temperature of only two or three degrees can produce an increase in the specific volume of the water and consequently a very rapid pressure rise capable of damaging the circuit. It is necessary to have a steam bubble in a water reactor circuit in order to absorb the volumetric change in the water. A boiling water reactor has steam voidage in the system and this is no problem, but a pressurised water reactor operates on sub-cooled water only and, in consequence, it is necessary to add to the circuit a piece of equipment designed to maintain the pressure constant. It is called a Pressuriser and consists of a pressure vessel maintained half full of boiling water at the circuit pressure. The water is maintained at temperature by heaters and the steam bubble above the water is cooled by a spray obtained from the primary circuit inlet leg. When a demand for load is placed on the reactor, heat is removed from the core and momentarily the temperature, and thus the pressure, drops. The heaters in the pressuriser switch on and boil off steam, thus increasing the circuit pressure. When the load is taken off the reactor an increase in temperature and pressure occurs, in which event the heaters shut off and the spray valve opens, steam is thus condensed and the circuit pressure is reduced. A similar arrangement is necessary in all sub-cooled liquid circuits. In the organic reactor this function is fulfilled by an expansion tank or degasifier.

## COMMENTARY

This paper is not strictly a technical paper and care has been taken to avoid the units of measurement which have evolved in the development of nuclear physics and radiology. It has been written as an introduction to the many facets of engineering which are involved in the design and production of a reactor, with particular reference to those reactor types best suited to the marine application at this time.

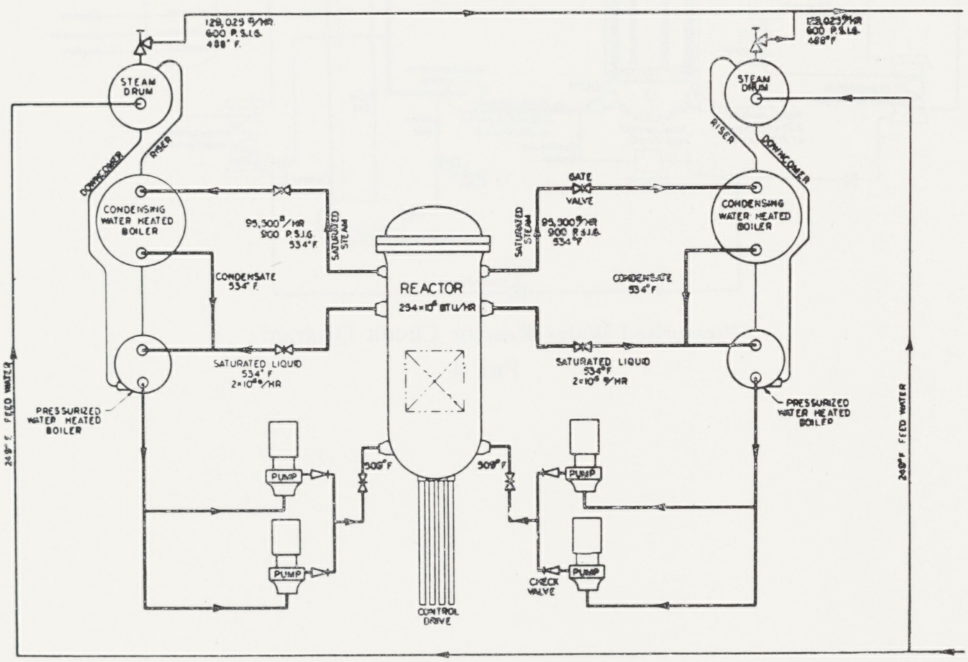
There are a number of technical papers on reactors presented to the Engineering Institutions which can be consulted if further information relating to any particular reactor type is required. Doubtless future Staff Association papers will deal with the particular problems of nuclear ship and nuclear machinery design and discuss how any particular design may best meet the Society's requirements for safe and reliable operation.

The line diagrams, Figs. 2, 3, and 4, contained at the end of the paper summarise the basic circuits of the three reactor types discussed, and again may be related to particular reactor design proposals to be found in the technical press.



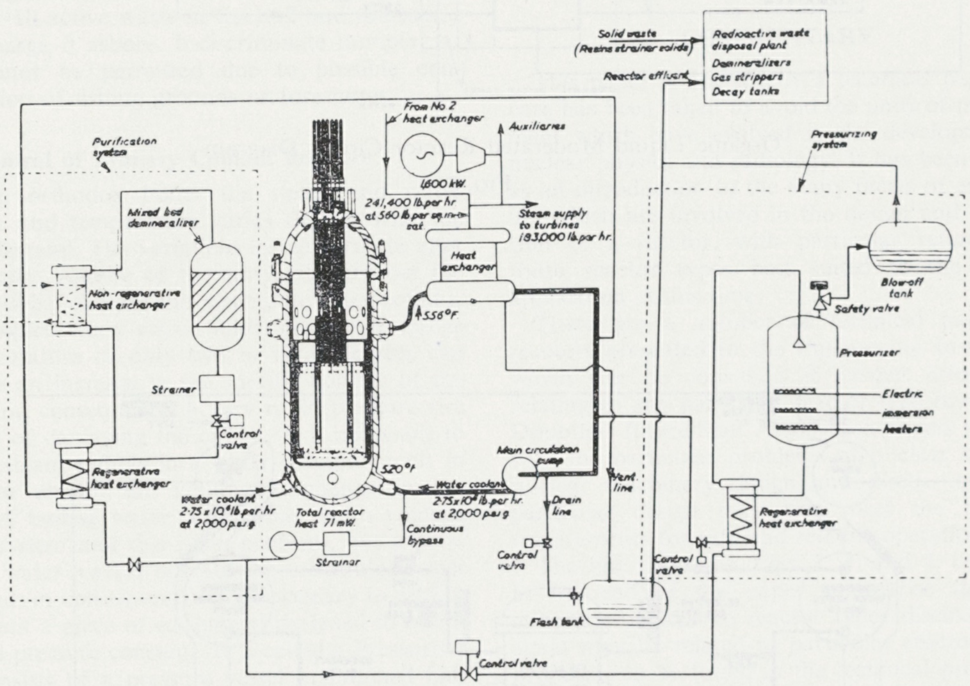

Organic Liquid Moderated Reactor Circuit Diagram

FIG. 2




Boiling Water Reactor Circuit Diagram

FIG. 3




Pressurised Water Reactor Circuit Diagram

FIG. 4

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# Lloyd's Register Staff Association

Session 1960-61

Paper No. 3

## Discussion

on

Mr. B. Hildrew's Paper

# NUCLEAR ENERGY— ITS SOURCE AND ITS APPLICATION TO MARINE ENGINEERING

LLOYD'S REGISTER OF SHIPPING

71, Fenchurch Street, LONDON, E.C.3

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Discussion on
Mr. B. Hildrew's Paper

# Nuclear Energy—Its Source and its Application to Marine Engineering

MR. G. P. SMEDLEY

Mr. Hildrew has presented clearly and concisely basic information of nuclear technology. The paper therefore forms a good introduction to nuclear power plants for ships. However, I feel that the application of nuclear reactors for the propulsion of merchant ships must be kept in true perspective.

A nuclear reactor only replaces oil fuel, its storage and equipment. In effect it is essentially an alternative source of heat. To be a success any new venture in marine engineering must show clear-cut advantages over existing equipment and practice. Moreover the advantages must outweigh any disadvantages which do not arise with proven and reliable machinery. Does a nuclear power reactor satisfy these requirements?

The advantages of nuclear powered submarines have been demonstrated beyond doubt by the U.S. Navy. This type of submarine has revolutionised the tactics of naval warfare. Unfortunately, the requirements of modern naval ships and merchant ships are so different that available types of nuclear power plants offer, at the best, only slight advantages over conventional plants and for a very few of the largest types of merchant ships. It must also be remembered that many important features of nuclear merchant ships have been determined by feasibility studies and have yet to be proved in practice.

At present, nuclear reactors appear to have many disadvantages for merchant ships and these could swamp any advantages which are claimed for atomic energy. Some of the disadvantages are as follows:—

(1) Very high cost of the nuclear plants and increased space requirements.

(2) High cost of the fuel elements and high capital investment represented by the core.

(3) Development costs are also very high. Moreover, it is unlikely that an existing reactor could be modified to take advantage of future developments.

(4) At present and so far as can be seen, nuclear propulsion is only a "proposition" for high powered ships. These represent a very small proportion of the ships of the merchant fleets. It is unlikely that the conversion of existing ships will be worth while until costs are much more reasonable.

The estimated operating costs of a high powered nuclear ship is comparable with known costs of an equivalent conventional ship, providing the number of nuclear reactors does not exceed one. This is not conducive to flexibility required in operation.

(5) Problems of operation arise if the reactor is shut down by accident or in an emergency. Poisoning of the core can result in serious delays before the reactor can be started up again. It must also be remembered that even a relatively minor fault in the parts of the reactor plant within the biological shield could put the plant out of action. These parts of the plant cannot be readily maintained, rectified and repaired.

(6) Highly trained and specialised technicians are required to look after a nuclear plant. At sea it is not possible to have specialists on hand who are familiar with all items of complicated and intricate equipment.

(7) Personnel must be protected against radiation from the reactor and when handling and transporting spent fuel elements and wastes. Moreover, reactor parts remain radioactive for a very long time after the plant is shut down. Final disposal of such plant when no longer required is likely to be difficult and expensive.

(8) The greatest disadvantage of all, however, is the inherent hazard of a nuclear plant. That things can go wrong and lead to the release of radioactive materials which cause fairly widespread contamination was shown by the incidents with the Windscale reactor and the materials test reactor in Pennsylvania. Safety regulations for nuclear ships must be comprehensive and strictly administered.

It will be some time before nuclear ships have unrestricted access to the many ports and waterways of the world. If he is faced with restrictions which limit the movements of ships, may cause undue delays and increased costs, a shipowner will not show enthusiasm for nuclear propulsion.

In my opinion, therefore, the nuclear power plant which offers a challenge to conventional main power plants of merchant ships is not yet in sight. Experience with land nuclear power plants is very limited. I consider that there is much to be gained from further experience and development of the power stations. At the same time, many seagoing problems can be resolved by nuclear submarines and other naval ships. I should like to have Mr. Hildrew's views on the matter.

It was anticipated in the early stages that abstracting the heat from the core of a reactor

and using it efficiently, would raise major difficulties. In just over a decade remarkable advances have been made in the technology of heat transfer, yet the difficulties with power reactors are far from resolved. So far, the heat from power reactors has been used to raise steam to drive turbines. The heat has been removed from the core by one of the following materials:—

(1) Water or steam (heavy or light water).

(2) Liquid metals.

(3) Organic materials.

(4) Carbon dioxide.

The choice of the medium for heat transfer must satisfy a number of conditions which are (a) stability under heat and irradiation, (b) compatibility with other materials in the circuit, (c) ease of handling and pumping round the circuit, (d) good thermal properties, (e) negligible or short life radioactivity. The above materials are the most suitable, but each has its limitations. In particular, liquid metals present the greatest problems and are unlikely to be used in marine type of reactors. With the others the conditions of the steam which is raised are poor. Helium-cooled, high-temperature reactors may be an answer but the gas is very expensive, it is difficult to prevent losses from the circuit and the problem of radioactivity appears to be increased.

Some degree of enrichment of fuels is essential for marine reactors. The sources of supply of such fuels could be restricted for certain types of reactors. It has been suggested that plutonium enrichment could be used with advantage. Does Mr. Hildrew know if elements of plutonium enriched fuel have been used in a power reactor?

In the paper reference is made to fast reactors of the breeder type. This, like many other nuclear propositions, sounds attractive but I should like to know if any fuel has been bred in the blanket of a fast reactor and also if it is fairly easy to convert such fuel into a form suitable for use.

### Mr. J. McCALLUM

The Author must be congratulated on presenting a remarkably simplified paper considering the complexity of the subject chosen. The recurring thread running throughout the discussion on irradiation damage to materials, shielding and the major accident is the uncertainty of calculation, particularly in relation to human response to harmful radiations. Are the limitations set for the concept of a major accident realistic, or, as the Author suggests, excessively pessimistic? How can one get an answer to a question of this kind! Some progress is being made in studies of the effects of irradiation on materials of construction, but it appears that the only way of confirming or disproving the major accident concept and human radiation tolerances is for an accident to take place in an under-designed reactor project. Of the accidents which have taken place in shore installations, most, if not all, have resulted from maloperation or a lack of observance of procedural rules. However many fool-proof devices are fitted, there will usually be an operator who can go one better.

The only disappointment associated with Mr. Hildrew's paper was the lack of animated cartoons depicting human little neutrons leading their own determined little existences, all unaware of the laws of probability. Perhaps the similarity to the Southern Railway peak hour was too distressing and the Author was probably well advised to stick to the snooker gambit which at least is an interesting departure from the more common billiards. His paper, while admittedly covering a wide field, must nevertheless hold the distinction of being the first technical work to discuss goldfish and tennis in the same breath.

### Mr. P. F. C. HORNE

First I would like to comment on a point made by Mr. Smedley in his contribution. Nuclear reactors need not be less flexible than conventional boilers. The n.s. *Savannah* has been designed to meet, without the use of the dumping facility, a manœuvring rate which is more than adequate for her ship type, and is probably greater than the propeller will usefully absorb. The electronic simulator gives every indication that these rates will be met.

Cleanliness of reactor components is a matter which deserves mention. Dirt or other foreign matter in a reactor circuit presents two problems. First, it absorbs neutrons and these are valuable since, for each fission we obtain slightly more than two neutrons. One of these is required to continue the chain reaction and the remainder will be absorbed in various materials in the core, moderator, control absorbers and coolant. Since we cannot avoid some absorptions due to the need for structural materials in the core and the need for moderator, control rods and coolant, any further losses are going to penalize the neutron economy of the reactor and require further, costly, enrichment of the fuel.

Secondly, dirt, together with corrosion products in the circuit, will become irradiated and may therefore cause a radiation hazard when routine maintenance is performed. In order to remove the activated "crud" resin bed demineralizers are usually fitted in the primary circuits of water-cooled reactors, and great care is required to avoid stagnant regions in primary circuits where trapping may occur. Similarly, for reasons of corrosion product activity, it is essential to ensure that impurities in structural materials having long half lives should not be permitted and for this reason a low cobalt content is specified for stainless steel used in core components, and in the case of the n.s. *Savannah* a value of ·04 per cent was obtained for the fuel element canning.

### Mr. J. MACLEOD

Having recently joined the Society, this is the first Staff Association meeting which I have attended. However, as I have worked in the

Atomic Energy Industry, I thought that I might make a brief contribution to the paper.

I think that Mr. Hildrew's paper provides a very good outline of the types of reactor available for marine propulsion and is certainly a very useful contribution to the Association.

The firm I was connected with before joining the Society is developing a design for a gas-cooled graphite-moderated reactor. This type of reactor is the one with which we, in this country, have had most experience and is inherently the safest. This is largely due to the use of $CO_2$ as a coolant. $CO_2$ does not become radio-activated and is a stable gas. Thus any leakage which does occur although of importance is not disastrous.

Two of the disadvantages which this reactor suffers from are extensive neutron leakage due to the open spaces for the gas flow (this necessitates the enrichment of the fuel to above four per cent.) and the fact that the pumping power required to circulate the $CO_2$ round the system can approach 10 per cent of the total reactor power.

The main problem in the design of a small marine reactor is one of space. In a land-based station there is room enough to fit things in and get a reasonable distance between points of high and low temperatures. This is very difficult in a small reactor and problems of differential movements and temperature gradients become very acute.

Probably the most difficult problem of all is how to hold the core firmly so that the channels through the graphite blocks remain in line and yet are still able to accommodate thermal expansion of the graphite due to high temperatures (over 1000° F. at the centre core), growth characteristics of graphite under irradiation, and also the shrinkage of the graphite blocks under prolonged irradiation.

This latter aspect necessitates a keyed core pressed firmly together so that each block on shrinking is still firmly in contact with its neighbour, and although shrinking, does not move its central channel hole out of line.

If the blocks were not pressed closely together, spaces would occur between the graphite blocks and "rattling" could occur under certain conditions.

In addition to the above, the core must be held against a shock load of 3g in any direction and still remain in working order. These conditions are very difficult to meet as you can well imagine. Needless to say there are many other problems of this kind which occur.

Great attention has to be paid to detail, no stresses can be neglected if they can possibly be estimated. For example, very careful selection of bellows units in the gas ducts is necessary and an estimation of the peak longitudinal stress levels in the convolutions is made to avoid any problems of stress relaxation which may occur in bellows of certain materials at high temperatures.

The foregoing comments give the briefest of outlines of some of the design considerations required in nuclear work.

Of the other reactors mentioned in the paper I am particularly interested in the B.W.R.

Mr. Hildrew stated that the B.W.R. introduces problems of power oscillations. Some experiments carried out in the U.S.A. would appear to have shown that steam voids up to 20 per cent can be tolerated without severe roughening of reactor output and also that the removal of moisture from the steam in the steam separators removed practically all of its neutron induced radioactivity.

Although control problems of this type of reactor are very difficult the possibility of delivering dry saturated steam direct to the turbines is very attractive. Perhaps Mr. Hildrew could enlarge a little on the future potential of this type of reactor.

In conclusion, it may be pointed out that as far as economy is concerned the sailing ship is still the most economical form of sea transport on the basis of cost per cargo mile. However, other factors are relevant which may favour the nuclear ship in the future as in the past the steam ship was favoured over sail.

## AUTHOR'S REPLY

Prior to answering the discussion I would like to address myself once more to the reader. The first portion of the paper is devoted to an attempt to explain how a nuclear reactor is evolved and why it should work. This is an extremely simplified version of the whole story and in order to reduce it to such simple terms it has been necessary to generalise. After re-reading the paper, it does appear that there are a number of items which are inadequately covered and, accordingly, I propose to attempt a brief survey of these points.

It should be clearly understood that the description of the atom on page 1 of the paper is particularly simplified and relates purely to those parts of the atom which are directly concerned with the nuclear reaction. There are, of course, a number of other particles or "phenomena" associated with the atom, some known, some inferred and some guessed at, reference to which has been deliberately omitted.

One question often posed by conventional engineers relates to shielding and asks why do we shield against radiation, and how effective is the shield provided?

External to the body, alpha radiation is readily shielded against. A sheet of paper or a piece of glass would protect an observer from such radiation, hence the use of an alpha emitter in the luminous paint used on watches, clocks, gauges, etc., is not a radiation hazard. Alpha radiation is an ingestion hazard and if an alpha emitter is swallowed or inhaled it will lodge itself in the body and over a period of years slowly damage the tissue. An example of this is the prevalence of jaw cancer among workers who originally painted luminous watch dials, as it was their practice to lick the brush between strokes in order to maintain a fine point on it. The

specifications for luminous paint are such that owners of watches with luminous dials may eat up to about one sixth of the dial without suffering long-term measurable radiation damage.

Direct beta radiation will damage body tissue, particularly delicate mechanisms such as the eye, but here again, beta radiation is easily shielded against, a thin metal plate or a few inches of polyethylene is adequate.

Gamma radiation is electro-magnetic, i.e., it is not a nuclear particle like alpha and beta radiation, but is merely an extension of the light spectrum down through shorter wavelengths, through X-rays to gamma rays. Gamma rays do not damage body tissue by direct impact, but the electrical field associated with them induces electrons to be ejected from the atom, this is termed "ionisation" of the material. Gamma rays can also break the valency bond which joins two or more atoms linked in a chemical compound and the re-linking of such atoms may not be in the conventional manner.

Free neutrons, and especially fast neutrons, produce nuclear damage in the atomic structure of materials which give rise to alpha, beta or gamma radiation.

The human frame is subject to, and capable of withstanding, a small degree of radiation. Some of this radiation is cosmic, i.e., it comes from outer space, and is unavoidable; a small amount is caused by background to our daily lives, e.g., clocks, X-ray machines, etc. Some, of course, is due to continued fall-out from atomic bombs. All these contributions are well within the tolerances which the General Medical Council consider acceptable to the body.

Radiation emanating from a power reactor is, of course, much greater than tolerance. The neutron intensity of the outer surface of a reactor pressure vessel is one billion ($10^{12}$) times greater than the permissible dose to the body and the gamma radiation is of the same order of intensity. Thus, an unshielded reactor in a ship would require the operator to be two miles away to reduce the dose rate to an acceptable limit. At 2,000 ft. a lethal dose would be received in fifteen minutes, at 100 ft. in one-fifth second. Even fifteen minutes after reactor shut-down, at 100 ft., a lethal dose would be received in thirty seconds. The effectiveness of shielding as protection of the body against this hazard can best be judged from the fact that the shielding round the U.S.S. *Nautilus* reactor is so effective it reduces the radiation level in the submarine to a minute amount. Due to the fact that the *Nautilus* is submerged when operational, background irradiation from cosmic sources is completely eliminated and, in consequence, the crew are exposed to a greater radiation dose when on leave ashore than they are when operating the vessel at sea.

Another question often asked by engineers is when an atom is fissioned, why do not all the energised particles decay immediately? Why is the decay exponential?

This is a difficult question to answer simply, but perhaps could be better understood by examining the human life span of those who work for the Society, always assuming we do not push the analogy too far. None of us can measure how long we are going to live, but life insurance companies are prepared to bet on it, basing their bet on statistical averages. Again, we have all got to die and if there were enough of us in the Society, one of us would die whilst you read this sentence, but this would not mean that we would all die at this moment.

Atoms do not age as we do and a radioactive atom always has the same chance of decaying or dying, unlike *homo sapiens,* who visibly gets older as time passes. Statistical analysis of the phenomenon indicates that the number of disintegrations is proportional to the number of radioactive atoms present. As even a small portion of material contains a vast number of atoms, if these atoms are radioactive they will decay in a purely random manner and we get an exponential decay.

It is convenient to give this effect in terms of half-life, i.e., the time required for one-half of the radioactive atoms present to decay. Usually a period of ten half-lives will reduce the most powerful source to an acceptable level.

The final point I would like to cover, which is not adequately brought out in the paper, is the influence of U.238 in a nuclear reactor. U.238 will fission if struck with a fast neutron possessing energy which is limited to a particularly narrow band. This phenomenon occurs at what is termed a "resonance" energy level and a U.238 atom on receipt of this particular quantum of energy will fission. As the neutron slows below this resonance level it might be absorbed by the U.238 at a number of lower energy levels. In such an event the U.238 will become radioactive and ultimately decay to plutonium. Such a neutron is lost to fission. Thus, in order to descend to the energy level which permits the thermal neutron to fission the U.235 isotope associated with the U.238 in the fuel, it is necessary to slow the neutron down by elastic collision in a hydrogenous medium and permit it to only approach the uranium fuel at an energy level which corresponds to a resonance level in the U.235 isotope, and it is this requirement which governs the matrix pitch of the fuel element in the moderator.

I have endeavoured to write the paper in such a way that when an engineer reads up to the point where Figure 1 appears, he actually has that configuration in his mind. It has, of course, not gone unremarked that the containment vessel and the reactor vessel will have round corners in the minds of Lloyd's Register surveyors.

Finally, may I repeat once more, that Figures 2, 3 and 4 are not related to the paper, but were included to indicate temperature and pressure conditions existing in possible marine reactors.

Mr. MacLeod's remarks relating to the gas-cooled reactor concept form an admirable

summary of the problems which installation in a ship would impose on this reactor type.

The problem of power oscillation in a marine B.W.R. is not only related to the steam voidage tolerated, but rather to the influences of ship motion on the volume of the steam voids and any consequent change in reactivity, resulting in such a change in volume. A number of rocking rigs have been built and a considerable amount of computer work has been devoted to trying to solve this problem, and it would appear that the reactor will be stable, but until a B.W.R. is installed and operating in a ship, absolute proof will not be forthcoming.

Recent published information of operational experience with a 30 MW direct cycle B.W.R. in America indicates that the radioactive particles present in the steam can be adequately removed by steam separators and contamination of the main turbine is negligible. The problems of installing a direct cycle plant in a ship are briefly:—

(a) The necessity of limiting personnel access to main turbines when on load;

(b) The necessity to instal the main turbines in the containment vessel or to build an additional containment vessel to surround the main turbines, in order to contain any major accident.

(c) The additional secondary shielding required to protect personnel under the major accident condition.

Mr. Smedley's contribution is not strictly related to the content of the paper, but his list of disadvantages associated with a nuclear ship is a very valid one. It is, of course, possible to raise counter-arguments to all the points he mentions and these might be summarised as follows:—

(1) Costs are bound to be high in first-off items of engineering whether built on land or in ships, and there is no doubt that considerable cost reduction is being achieved in the land-based gas-cooled reactor field as experience is being built up in this country.

The space requirement is not too great a problem in the context of ships of 20,000 s.h.p. and upwards. Small ship installations are not feasible at this time.

(2) The higher cost of fuel is due, in part, to the arbitrary price fixed on enriched fuel by the controlling Governments and due, also, to the numerous varieties of fuel element design evolved by the industry. If a common fuel element could be agreed, considerable cost reduction would be effected, with only minor loss in reactor optimisation.

(3) Development costs are high, but in the context of the reactor core it is possible to design to take advantage of future developments and this is often done in hydrogenous moderated reactors.

(4) The capital and operating costs of a nuclear ship must offer a better return than a conventional ship before a buyer would be interested. At present an economic nuclear ship is not possible. However, experience must be bought in the constructional and operational field and it is a matter of political judgment at what point a Government must decide to support the building of the first ship in order to build up a nucleus of experience in what may be a major industry of the country concerned.

(5) No major operational problem affecting restarting arises consequent upon accidental reactor shut-down. Further, although it can be argued that reactor design is too intricate to provide reliability, this has certainly not been demonstrated in the American submarine programme.

(6) Training of personnel to operate marine reactors safely and reliably is possible and, again, we must point to American experience. The shipowner's problem will be to persuade the highly trained personnel required to remain at sea.

(7) There are international regulations governing the transport of spent fuel elements and no unacceptable hazard will be involved. The disposal of discarded plant is, of course, a problem, but the monuments Great Britain has built at Calder and Chapelcross will ultimately present a similar problem.

(8) If the inherent hazard of nuclear plant is a bar, obviously we should never have started to build land-based reactors. Nuclear ships, it can be argued, are a hazard in ports which are always located in populated areas. The advantage which the ship does possess is that it can always be towed away to a remote area.

The restrictions imposed on the movement of nuclear ships have not yet been defined, but until such ships are operating they never will be defined. The necessity of examining the problems associated with admitting the *Savannah* into the ports of the world is forcing requirements to be made on both a national and international basis.

It is agreed that further experience and development of nuclear power stations is desirable, but the policy in the U.K. of devoting all its industrial talent to large gas-cooled reactors is of little immediate value to a future nuclear marine industry.

The most promising line of reactor type development in this country probably lies in the building of an advanced B.W.R. and developing it through steam cooling. Ultimate development to high steam temperatures would marry in with the gas reactor technology built up in this country.

Plutonium fuel is virtually untried except in small research reactors and one of its problems is its geometric instability during irradiation. Enrichment by spiking uranium elements with plutonium is being developed and, again at research reactor level, is showing considerable promise.

The reference to the breeder reactor in the paper is not as a possible marine reactor type, but merely for completeness in discussing the reactor fuels available. The breeding of fuel in a fast reactor blanket has not yet been achieved in practice. The conversion of such fuel into a

form suitable for use is not easily achieved, but recovery plants have been built, both in Great Britain and in America, and the economics of such plants will be proved in practice in the near future.

Mr. Horne's comments on the cleanliness requirements were very relevant to the problems which will face the marine engine builders and shipbuilders of this country if they ever undertake nuclear work. The cleanliness standards imposed on the naval reactors building in this country is providing a nucleus of personnel with experience of construction in clean conditions.

Mr. McCallum's proposal that we should have a major accident in order to prove the adequacy or otherwise of the calculations and to determine its effect on the population, is a rather exotic idea. A more orthodox engineering approach for any installation would be to design out those defects which could lead to major accidents. The design experience of reactors built, plus the considerable field covered by engineers examining reactor safety problems, is steadily reducing the unknown and the arbitrary parameters placed on the major accident problem in the early days of reactors are due for technical re-appraisal.

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For Private Circulation amongst the Staff only

# Lloyd's Register Staff Association

Session 1960-61

Paper No. 5

# BRAZIL

by

I. G. SLATER, Ph.D., M.Sc., F.I.M., C.I.Mech.E.

LLOYD'S REGISTER OF SHIPPING

71, Fenchurch Street, LONDON, E.C.3

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# Brazil

**By I. G. Slater, Ph.D., M.Sc., F.I.M., C.I.Mech.E.**

A year ago I had the pleasure and privilege to lecture to your Staff Association on "Russia", and on this occasion I am to talk about Brazil. My professional interests are mainly educational and technological but I hope that I can colour my lecture by including a few impressions of the habits, culture and ways of life of Brazilians which I saw and met on a recent visit to their exciting land. To say that the two countries, Brazil and Russia, present a formidable contrast is indeed a vast under-statement and perhaps the proximity of my visits to these two countries will exercise to good effect my ability to sum up some of the main attractions of Brazil.

A substantial proportion of my talk will be about the problems which face Brazil in exploiting her own natural wealth and in developing her technology quickly and effectively whereby her standards of living can be raised from the unfortunately low levels they presently enjoy. I speak here of standards of living from the materialistic point of view, for it is well to recognise that many of the greatest things in life can flourish almost on plain bread and water, providing that the people concerned have the right temperament and appreciation.

To emphasise further this problem of standards (materialistic ones) a glance at the graph (Fig. 1) will show that the Brazilians consume per head of population only one-tenth the amount of steel we use in this country. This same ratio holds for most of the other materials commonly used for the pots, pans, plumbing, hardware, transport, tools, television and so on, of modern civilisation. We must modify this overall impression of averages by observing that there are sectors in Brazil where standards are happily high consequent on concentrations of wealth but there are many sectors where the reverse is readily visible. Much of the country is, of course, wild and undeveloped and where perhaps many of our modern amenities would be out of place or unwelcome.

Impressions which one may gather of any country are greatly circumscribed by personal factors. It has also been my own impression over the years that the same person would tell a very different story indeed if his stay had been of a year's duration rather than, say, of one month. My own recent stay was of three months and, thanks to the generosity of my hosts, the Brazilian National Research Council, my wife was able to join me in this expedition. Perhaps in this way we packed into our joint experience far more than usual, for many more doors were opened to us, certainly on the social side, than otherwise would have been the case. Rio de Janeiro is now but an overnight flight from London and travel when in Brazil relies exclusively on their excellent air travel facilities especially if one is in a hurry. My set task in Brazil was to see as much as possible of their technological effort, particularly in the metallurgical field, to visit certain educational and scientific establishments, to give a few lectures and to dispense a reasonable amount of advice. Before retailing impressions of these matters, it will be useful if I outline reasonably briefly something of the history and present economic background of the country.

FOOTNOTE.—Substance of a lecture to be given to Lloyd's Register Staff Association, London, on 7th February, 1961.

## HISTORY

In A.D. 1500 the Portuguese Admiral, Pedro Alvares Cabral, in making a passage from Lisbon to India sailed much further west than usual in order to clear the doldrums at about latitude 17° S. On Easter Day of that year he sighted land and discovered a native population in the "Stone Age" with no domestic animals and little agriculture. The new land was neglected at first since there were no "visible" minerals and Brazil owes its name to a red wood containing a red dye. Sugar was to become the basis of the country's economy for two centuries, mainly in the province of Pernambuco, but was slow to develop. Slave labour was the order of the day in those times and the Brazilian Indian was remarkably unco-operative in knuckling under to the new masters. However, the Portuguese in 1550 began to import African slaves on the labours of whom the country grew and prospered.

French and Dutch adventurers attempted rival colonisation but were thrown out repeatedly by the valiant Portuguese so that by 1654 they settled down to undisputed possession. For this reason, the national language of Brazil is traditional Portuguese. About this time groups of adventurers known as Bandeirantes began to explore the vast hinterland of Brazil; perhaps one of the most arduous efforts in the history of mankind in his search for material gain. The terrain is of the toughest and ranges from the lush tropical jungles of the Amazon basin to the wild and unpredictable country of the Mato Grosso and to the more amenable lands of the south. Effective exploration of many countries has been possible thanks to numerous rivers running tranquilly to the seaboard. Anyone who has read of Colonel Fawcett's travels will appreciate that Brazil offers much less happy facilities for travel by water!

Just before the turn of the 17th century gold was discovered in large quantities in Minas Gerais and the gold rush which followed denuded labour from everywhere. Sugar economy gave way to a golden age and up to the time of the Californian

*Per capita* **gross product and apparent consumption of steel, 1955**

LOGARITHMIC SCALE

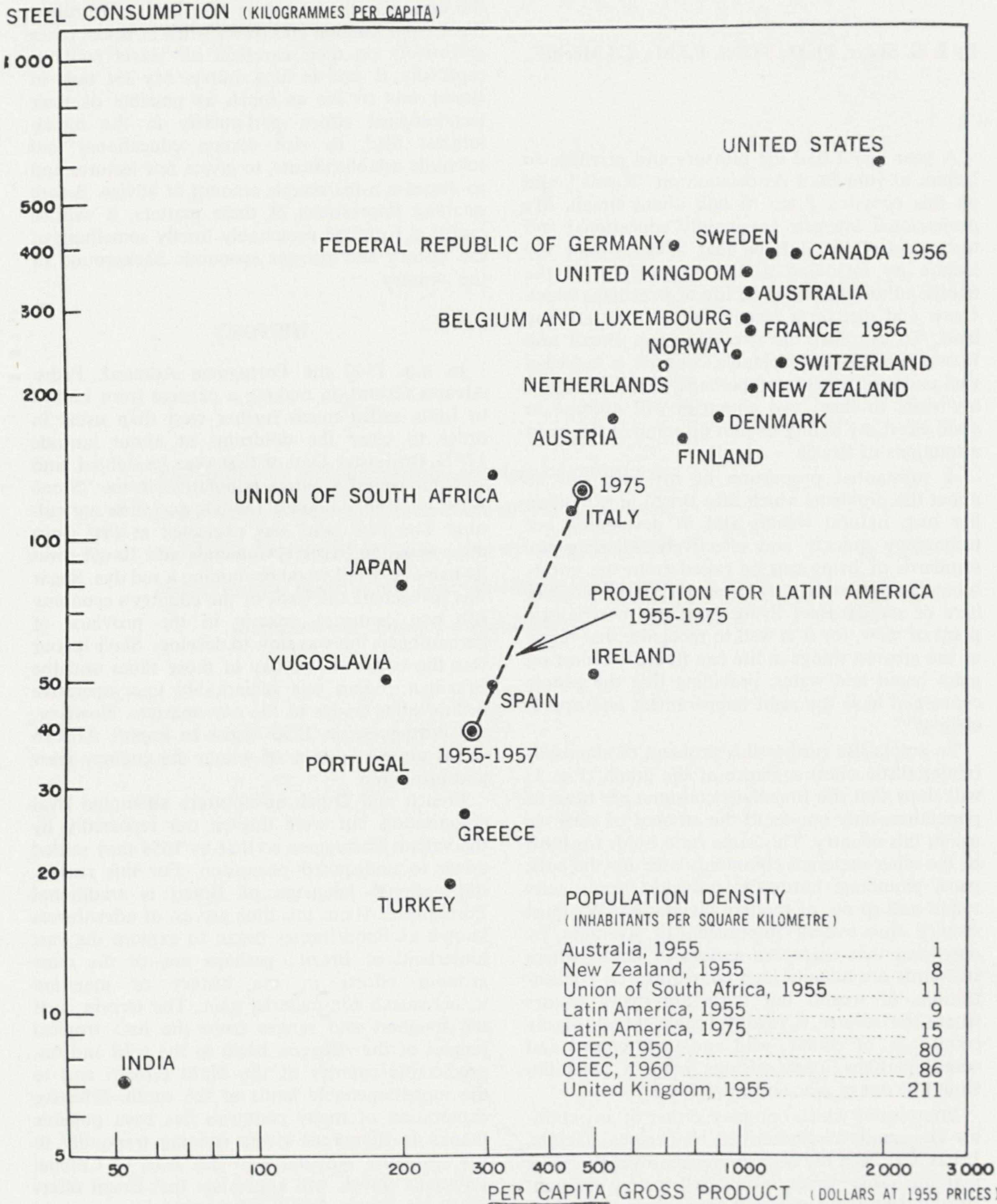


Fig. 1 Graph showing the consumption of steel per year per person (1955) in various countries. Note that the graph also includes the projected expansion for the Latin American countries over the years 1955 to 1975

gold rush of 1849, Brazil shipped more gold than the rest of the new world. At this time, the alluvial gold deposits petered out and, significantly enough, diamonds were then discovered in really substantial amounts.

Thanks to the treaty of 1750 between Portugal and Spain, the frontiers of Brazil were established to provide the fourth largest country in the world with an area of some 3 to 4 million square miles. Later in this eighteenth century the rumblings began to be heard (so familiar to us these days) of a colony wishing to shake off its subordination to its mother country. The Napoleonic wars halted this movement for a time but consequent on one of those queer twists of history, freedom and independence came within sight. Naturally, the British Navy had a hand in this for it was our Fleet which escorted the Portuguese Royal Family to Brazil for safe keeping in 1808 when Napoleon invaded Portugal. There they stayed in Rio to give a great stimulus to industry, arts, commerce and education. In 1821 the Portuguese king returned home leaving his son, Don Petro, to rule as Regent and who after a mere year in this role, asserted his independence and became the Emperor of Brazil. His son carried on in this tradition until 1889 when a Republic was proclaimed.

The history of the Republic from 1889 to 1930 was comparatively uneventful when a minor revolution with a minimum of bloodshed saw a radical change in leadership in President Vargas. In more recent times, the country has developed and prospered under President Juscelino Kubitschek.

## PRESENT-DAY ECONOMIC BACKGROUND

### Natural Resources

Modern industrialised states are not built in a day and we, of the more fortunate countries of the western civilisations, owe much to our ancestors over several centuries. They have built up for us not only our democratic way of life but also the sinews of our industrial strength with its all-powerful backing of science and technology. In many respects Brazil has been thrown into this complexity a century or two later than has been our more fortunate lot and the task is to catch up with us without destroying certain of the more human factors and ways of life which we regard as a precious heritage. Certain countries, notably to the East, have had chosen for them other less democratic ways of making rapid material progress, but this is another story.

The strength of Brazil's prospects lies in the nature and determination of her peoples combined with the exploitation of her natural resources. Some of these resources are a bit difficult to get at because of the problems of the terrain and the very size of the country. A few statistics of both developed and undeveloped resources will illustrate this matter to advantage.

To touch on edible vegetation for a start, more than half the area of the country is tropical forest whilst another 22 per cent is scrub and another 10 per cent is cactus desert. Coastal vegetation is a mere 1·1 per cent. To bring more of the land under controlled cultivation is a prime requirement but the opportunities are immense, for with the range of climates available it should be possible to grow virtually everything of interest to man's taste or digestion. Coffee, of course, looms large in Brazilian economy and in fact in recent years has been responsible for well over half of the value of the country's exports. Other major exports include raw cotton (about 15 per cent) and cocoa (about 10 per cent) whilst sugar, the mainstay of the earlier export economy of the country, is a mere 1 per cent or so.

To mention the other main crops of the country, and which are consumed in the main by the Brazilians themselves, rice, corn, beans, manioc and bananas, come high in the list of values. Further, to illustrate the potential attractiveness of the Brazilian tastes in foodstuffs, it is useful to include oranges, grapes, sweet potatoes, coconuts and other nuts in variety, mangoes, avocadoes, green pepper and other spices, melons, peaches, bamboo shoots and so on. Like any other well-civilised country Brazil rejoices in many national dishes and to mention examples (which certainly are not to be found in the pages of Mrs. Beeton) there are "Ferjoada Completa", popular in the state of Minas Gerais, which includes black beans with sausage and other pork derivatives boiled together with orange slices with a good dose of pepper, or if one prefers a dessert, "Mineiro com Bota" which comprises melted cheese with banana slices, butter, guava jelly and sugar, all in layers.

Turning to other types of natural resources in Brazil, the account is a little more complex, for Brazil has yet to do an enormous amount of exploring and prospecting. The exploitation of these resources after they have been located often presents enormous problems in transport because of the difficult terrain and the fact that so much of the country has yet to be opened up with roads and railways.

The fuel problem is at present a difficult one for only two million tons of coal per year are mined whilst most of the fuel oil has to be imported. A very substantial effort is being made to discover oil resources in the country and this is a very expensive and speculative business. On the other hand, Brazil abounds in rich iron ore, whole mountains of it; in fact, one-quarter of the world's known resources are to be found in the states of Minas Gerais and Mato Grosso. To smelt some of this, for coke is very limited, hundreds of thousands of acres have been devoted to the growing of eucalyptus trees to produce charcoal. It seems a pity that we have not worked out in some practical way a scheme to ship out our abundant British coke and return home with fat cargoes of choice Brazilian iron ore. Substantial resources exist in water power for the generation of electricity but development is slow, particularly since the problem of capital or credit for investment is limited.

Metals and minerals obviously abound, but few of them have yet been exploited in any really substantial way. Gold and diamonds have dwindled to relatively low levels in the economy. The ores of the more common non-ferrous metals are as yet limited, with perhaps the exception of bauxite, the ore of aluminium. A few minerals, notably beryl, manganese ore and rock crystal make a useful contribution to the world's usage of these materials. Semi-precious stones including zircon, beryl, amethyst, topaz, tourmaline and aquamarine should not be omitted from any list of characteristic Brazilian minerals.

**Industrial Resources**

Brazil has had to draw largely on other countries for the necessary crafts and technologies on which to build up her industrial resources. It is happy to think that our own country has played a prominent part in this, especially in the earlier years. In more recent times other countries including the U.S.A., Germany and Italy have taken an ever-increasing interest in this matter. Thus, many of the newer Brazilian industrial enterprises have strong commercial links with these countries consequent on the introduction of manufacturing equipment and technical guidance from abroad. In this manner, large and progressive industrial organisations with excellent manufacturing resources have sprung up in such centres as Sao Paulo, Rio de Janeiro and Belo Horizonte, concerning themselves with metallurgical production, transport, electrical goods, textiles, chemicals and generally all those manufactures of prime concern to the modern way of life. However, much more remains to be done to bring average standards of living up to a reasonable level.

Other vital sinews in the welfare of industrial progress are cash and credit. These are problems which are acute enough in our own British economy. The embarrassments in Brazil are much larger and much more difficult to solve, certainly on a short term basis. The balance of overseas trade is such as to require the utmost economy in the purchase by Brazil of foreign goods and equipment. Thus purchases must be limited to vital essentials and especially to manufacturing equipment and the like which at present cannot be built from native resources. In many cases, the Brazilians have secured manufacturing equipment from overseas on favourable credit terms which reflect in some measure the faith of the foreign country in the ultimate prosperity and commercial stability of Brazil. However, the country has seen an inflationary period in recent years and the value of the currency on the free exchange has fallen sadly.

**Education**

Another vital vector in the prosperity of a country is education. There are many facets to education ranging from the purely cultural to the extremely materialistic. Modern industrial activities require the services of properly trained and experienced scientists and technologists and Brazil is woefully short of such men. Only a relatively small handful of technologists is being trained each year in Brazil as compared with three-quarters of a million in Russia.

About 100,000 students in Brazil are receiving higher education but of these only 2 or 3 per cent are studying the pure sciences and about a similar number the applied sciences. In contrast to these lowly numbers, law students number nearly 20 per cent of the total whilst medicine and dentistry number about another 15 per cent. This distribution is akin to the state of affairs in the Universities in this country at the start of the present century.

This problem of attracting more students to study science and technology in Brazil involves a number of social issues peculiar to the country. Brazilian family influences and traditional ways of life usually suggest that the sons of the more wealthy families, who can afford University education, should be attracted more to the cultural or administrative studies. Engineering more usually means some down-to-earth activities with one's own hands, especially in earlier years. However, despite their limited numbers, I have nothing less than profound admiration for the work I saw in the technological departments of the Universities and Colleges I visited, both in teaching and in research. Enthusiasm and devotion to duty abounds in these places at a level which would satisfy the most exacting of us in this country or our fellow scientists in Germany, the U.S.A. or Russia. The problem is simply one of numbers.

Thus, Brazil's educational system bears the burden of having crystallised in a surrounding of aristocracy but is certainly now in a state of gradual re-formation. Primary education is free, as is secondary education, where the teaching is in the hands of the public authorities. However, these resources are somewhat limited at present, relative to the scope offered here in Britain. Private education with fee - paying students flourishes at all levels, and prospects depend, in measure, on family finances.

At the advanced level, the development of the Craft and Technical Colleges, as distinct from the Universities, is limited and compares most unfavourably with the scope and standards which have been provided here. Education certainly demands imagination, investment and sacrifice and Brazil's problems in this respect have to be matched up with the demands of industrial and social requirements. It is clear to me that Brazil must devote very much more of her resources to education, particularly in the technical and technological fields if material prosperity is to arrive.

## IMPRESSIONS OF BRAZILIAN PEOPLE AND WAYS OF LIFE

My observations on these most absorbing topics are necessarily coloured by the people we met and the places we visited and with this excuse I will plunge into the hazards of a limited pencil sketch. At the outset it is right to note that Brazil has a number of very rich people together with lots of

poor. Well over 90 per cent of them are of the Roman Catholic faith and their traditional devotion is well evidenced by their beautiful churches. In matters of racial origin, some 60 per cent or more are white, 26 per cent are coloured, 11 per cent black and half per cent yellow—to quote the guide book. Racial discrimination is not known, whilst a rapid increment in population (at present 60 million) is assured by a really bumper birth rate of 43 per 1,000. This latter feature is well demonstrated by the population of Belo Horizonte where half the people are under 20 years of age.

By nature, the people of Brazil are progressive in outlook, optimistic, volatile, affectionate, witty and have a love of life and good living. Old-world courtesy abounds, ladies' hands are kissed on meeting, whilst other forms of natural politeness in human relations are in great contrast to the casualness of common behaviour known to us nearer home. Their ability to speak foreign languages certainly puts the average Britisher to shame, for quite a dozen different audiences were happy to hear me lecture to them in plain English.

The coining of expressions in the Portuguese language is a happy pastime. Thus the rather outsize buses of Rio are known as "queue swallowers", a malicious person is a "tiger's friend", a V.I.P. is a "rain maker", whilst colours are often employed to express specific emotions or attitudes. The fruit family is well deployed in reference to personal beauty and it is useful to note that our English peach becomes a Brazilian "grape". To see a Brazilian in conversational activity is quite an experience, for the hands fly with great dexterity around head and shoulders and occasionally well at the back of the opposite number.

The family unit is very important to the Brazilian and care is taken to conserve its integrity especially amongst the upper classes. It is understood that the women acknowledge their husbands as head of the family, preferring to use their influence subtly. It is also on record that whilst the husband does not feel obliged to tell what goes on at his office, the wife, on the contrary, is expected to give him an account of all that happens at home while he is out. Girls marry young and in a general way the parents' opinions are still of great influence in their choice.

In business dealings, the personal contact is often a vital element, for the Brazilian likes to know the nature and substance of the man with whom he is trading. This introduces complications which may be hard to solve especially where modern high pressure salesmanship is likely to operate. One aspect of the way of life which may perplex the visitor quite a lot is the apparently dilatory way negotiations may progress for a time followed by an amazing spurt of activity when the Brazilian displays his wonderful ability to get things fixed in a matter of minutes. It is wise to know that there are certain traditions in Brazilian commerce where the rights of those on the purchasing side are to be observed with care.

Very often, men of property, business and even the professions, have more than one major interest and it is not unknown for the harassed husband to have to rush to his first office at 8.0 a.m., followed by a move to his second office at 11.0 a.m. and subsequently to his several other enterprises throughout the day. A few of the larger industrial undertakings belong to the Government but private enterprise is the life blood of most of industry, a very substantial proportion of which is privately owned. In consequence, dealings on the Stock Exchange are at present relatively modest.

Brazil possesses some of the best architects in the world as is clearly evident from the brilliant buildings on contemporary lines to be found in the larger cities. More usually, concrete is the main material of construction. Some of the older buildings of the earlier settlement possess no less equal charm and obviously derive their inspiration from the Portuguese tradition. One city, Oro Preto in the State of Minas Gerais, retains nearly intact its great richness of earlier colonial days in churches, chapels, public buildings and residences and is indeed a magnificent repository of the arts and crafts of those times.

For the more ordinary man, sport is an absorbing attraction, especially football. Thus the three-mile-long Copacabana beach at Rio, touched by the rolling waves from the Antarctic to the south and flanked by skyscraper hotels and apartments on the other side, comprises a score or more impromptu soccer pitches. Bare feet are the main propellant for the ball and the score of bruised and battered toes must be legion for the vigour and skill put into the game would delight any British fan. Love of the horse is yet another attraction, be it in racing, jumping or polo.

Outside the larger towns, travel may present certain problems for macadamised roads are few and rail transport limited. Dirt roads abound and, providing that the rainy season is not at hand, it is amazing to see how well these tracks can be maintained, thanks to the availability of modern earth-moving equipment. Air travel has solved a number of transport problems and the Brazilians are rapidly expanding the scope of their several already well developed air lines. The new capital, Brasilia, which has been founded in more recent times and is located well in the interior, depends in substantial measure on air transport for its main contacts with the outside world.

**The Future**

At the end of this very limited discourse on Brazil and which must be full of shortcomings, it may be useful if I speculate briefly on the future. Political stability is, of course, a very vital issue in such speculations and in this I pin much faith on the Brazilian character and especially its individualistic outlook where the rights of each

and every man are emphasised in every way. I much doubt if this would succumb to a totalitarian régime in the immediate years ahead and the main task of the present democratic republic is to sort itself out and to mature.

I trust that I have made it clear that Brazil abounds in natural wealth and the task is to open up the country so that mineral deposits can be further exploited and its vegetative resources expanded many times. Industrial progress will depend on a number of factors, not the least on the availability of more and more technologists and scientists, and on capital and credit. We, of the better endowed countries, must do very much more than at present, in helping out, particularly in technological knowledge and experience. In such work it is vital we realise that the upsurge in recent years of nationalistic feelings merits careful appreciation, for the Brazilian, in common with many other races, jealously guards his rights and his property.

Thus our "helping out" has got to be of the right calibre in quality as in quantity and speed is essential in getting things going. Given common sense and a measure of fortune, times of great material prosperity cannot be so far ahead, perhaps two or three decades. In wishing the Brazilians all success in this task, may we hope that they will retain not only their vigour and confidence but also their affectionate and charming ways of personal contact which is a happy heritage indeed.

Fig. 2 Up country in the earlier days, as it might have been, and with apologies to Col. Fawcett!

Fig. 3 Native houses with thatched roofs a few miles from Rio

Fig. 4 Earlier ecclesiastical architecture to be found at Oro Preto

Fig. 5 Modern urban life in Sao Paulo—the coffee drinker

Fig. 6

Panning for gold or diamonds ; weary and unrewarding work except for the lucky ones

Fig. 7

Modern Rio from the window

Fig. 8 Fabulous Copacabana Beach with its impromptu soccer pitches

Fig. 9 Graceful architecture in concrete

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Lloyd's Register
Staff Association

Session 1960 - 61
Paper No. 6

# THE DESIGN AND CLASSIFICATION OF A NUCLEAR POWERED SHIP

by

J. McCALLUM, B.Sc.

LLOYD'S REGISTER OF SHIPPING
71, Fenchurch Street, LONDON, E.C.3

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# The Design and Classification of a Nuclear Powered Ship

By J. McCallum, B.Sc.

### 1. Introduction

The problem of how to use atomic energy to the best advantage has not as yet been satisfactorily solved. High reactor power, almost unlimited space for development and immobility of foundations are valuable assets in the construction of an economic shore-based installation, and yet, with all these advantages in their favour, our nuclear power stations are barely offering economic parity with fossil-fired installations, and even this is prejudiced by the (possibly temporary) drop in conventional fuel prices.

So it can be judged what difficulties face the designers of a nuclear ship with its relatively low power demand, restricted spaces and mobile machinery platform. Under these conditions, considerable advances will have to be made in reactor engineering techniques before a nuclear ship can become fully competitive with her conventionally powered sister. On the other hand, the concept of a marine nuclear power plant must not be shrugged off as a pipe-dream. It has powerful latent advantages in relation to its marine environment which put it in quite a different category from either the conventionally fired marine boiler or the shore-based reactor plant. For example, long voyage conventionally powered ships such as super tankers or passenger liners carry large quantities—measured in thousands of tons—of oil fuel, displacing a similar quantity of revenue-carrying cargo in the case of tankers or reducing speed by virtue of increased draught in passenger ships. The nuclear ship will be untrammelled by fuel requirements of this kind.

When economic parity is first achieved, it will almost certainly be in the high power range and probably in a passenger ship type, but it is likely that safety considerations will require a preliminary proving period for the reactor system in another type of ship.

In this discussion the possibilities of designing a nuclear ship will be examined with particular reference to the Provisional Rules for Nuclear Ships recently published by this Society.

The design of a tanker and passenger ship—both, for the moment, paper studies—and later the American nuclear passenger-cargo ship, the *Savannah*, will be considered in turn. In all cases the discussion is concerned primarily with ship design, although reference will have to be made to reactor engineering requirements.

### 2. General Aspects of Nuclear Ship Design

Basically, differences in design between nuclear and conventional ships can be summarised as being due to the following features:—

(i) A nuclear ship requires virtually no conventional fuel if it is powered by more than one reactor, and very little fuel for emergency propulsion and ship's services if only one reactor and a "take-you-home" emergency unit are installed. This alters the entire concept of design from the viewpoints of trim, strength and stability. The problem of the ship designer is simplified, to a certain extent, in that the burnt-out condition is virtually the same as the departure condition.

(ii) The necessity for the provision of collision and grounding protection in the nuclear ship in way of the reactor compartment to prevent possible serious damage to the reactor containment and internals, and the escape of radioactive elements to the atmosphere.

(iii) The provision of a containment vessel surrounding the reactor pressure vessel, primary circuit and principal reactor components to contain fission products in the event of a nuclear accident.

In addition, the recent Safety of Life at Sea Conference in London (1960)[1], included in its findings a recommendation that a nuclear ship, whether passenger or cargo, should be constructed to a two-compartment standard of sub-division—that is, that the ship should remain afloat and have sufficient stability when not less than any two adjacent main watertight compartments are flooded.

A realistic minimum power output for a marine reactor planned at the present stage of development is in the region of 20,000 s.h.p. Above this value, the power to weight and power to cost ratios will increase, and below 20,000 s.h.p. these ratios will become altogether prohibitive. For any hope at all of economic development, we are therefore restricted, at the moment, to consideration of ships which can make use of a power in excess of 20,000 s.h.p.

### 3. Provisional Rules for Nuclear Ships

For classification with this Society, any nuclear ship must satisfy the requirements of the conventional Rules for Steel Ships, and, in addition, the applicable clauses of the Provisional Rules for Nuclear Ships. In this connection, it should be remembered that these rules have been issued primarily to give guidance, and that in this developing technology, they must be regarded as completely flexible. Proposals which do not satisfy

[1] For references, see page 9.

the Rule requirements, but incorporate compensating features, will be specially considered for approval.

The Nuclear Rules require certain parts of the bottom and side shell and strength deck plating to be of special quality steel in addition to the material requirements of the conventional Rules. The scantlings of the deck and shell are to be such that the longitudinal strength of the ship will exceed by 10 per cent the requirements of the Rules for the class of ship, and the midship thicknesses of the principal plated members are to extend over the midship half length.

The continuity of longitudinal strength members is emphasised, particularly in the region of the reactor compartment where discontinuities are liable to occur. These are mainly due to the excess of material provided in the vicinity of the reactor space to provide supports for the reactor pressure vessel and containment and also protection against grounding and collision damage; fuelling and de-fuelling requirements will usually demand a hatch of between 10 and 20 ft. in diameter through the strength deck. These irregularities will require very careful design to eliminate the production of "hard spots" at the ends of the reactor compartment.

The stiffness in way of the reactor compartment will be made even greater if thick shielding is associated with the longitudinal members of the ship's structure, and for this reason the Society requires that thick steel or sandwich structures should be constructed separately from the main hull girder, and that, if concrete is used, this should take the form of blocks rather than mass concrete, both from the aspect of allowing free deflection of the ship and of limiting damage to the containment vessel.

Reactor components and supports should be designed on the basis of an impact acceleration of 3 g in any direction applied through the supports and other connections to the ship's structure. This figure has been adopted after a general consideration of the types of impact to which a ship's hull can be subjected, and although little information is available on the immediate effects of collision damage, and while it is realised that fairly rapid attenuation of acceleration forces takes place in an elastic structure such as a ship, it is not considered that this blanket requirement of 3 g imposes any serious penalty on the designer. Recent experiments carried out by the Japanese[2] have shown that, on one occasion in heavy weather out of three voyages, 3 g was recorded due to slamming on the fore deck. Of course, the reactor will never be placed on the forecastle, but it is well to remember that the slamming impact giving rise to this acceleration at the deck occurred on the under part of the ship, and if attenuation took place, local accelerations around the bottom forward must have been very high indeed.

The structure of the ship below the reactor and at the sides in way of the containment protection will also have to be specially considered from the aspect of absorbing the energy of collision and grounding forces. The Rules require a double bottom not less than 6 ft. in depth and it is suggested that a longitudinal system of framing should be incorporated in association with bottom transverses.

The Rules also require special submissions for the design of side framing in way of the reactor compartment and it is proposed to examine this in greater detail in a later section. It should be noted in passing, however, that a longitudinal bulkhead must be fitted between the side shell and containment vessel, and that the wing space contained between the longitudinal bulkhead and the side shell must be a void space, although water may be carried in the double bottom below the reactor compartment.

As a protection against the effects of damage caused by fire or explosion in the ship's cargo, all cargo spaces are required to be separated from the reactor compartment by a cofferdam at least 5 ft. in length. Machinery spaces, control rooms, pump rooms and the like will be regarded as equivalent to cofferdams in this context.

Certain requirements are proposed relating to the support of the containment vessel, but these will be discussed in a later section.

When the structure is completed, the reactor compartment will be air tested to a pressure of 4 p.s.i.g., and arrangements for the ventilation of this compartment are to be provided in such a way that its gastight integrity is unimpaired.

The nuclear ship is to be fitted with two entirely independent means of steering, with duplicated controls from the bridge to the steering gear and duplicated arrangements from the source of power. In common with modern practice in large passenger ships, a push button starter for the alternative steering system should be provided in the wheelhouse and an alarm warning system to give notice of the failure of the main steering system. Alternatively, the change-over to the emergency system may be fully automatic as desired.

Unless two or more reactors capable of independent operation are fitted, a power supply separate from and independent of the nuclear machinery must be available.

This power supply should be capable of propelling the ship at a speed sufficient to maintain headway in rough weather, and it is considered that a speed of about six knots in still water will satisfy this requirement. A range of 1,000 miles is required.

### 4. Form and Speed

When nuclear power was first proposed for ships, the prospect of unlimited power led many to believe that very high speeds would be possible. There is no doubt that higher speeds are possible, but at a cost. Just as increased power means increased fuel consumption and higher prime cost in conventionally powered ships, so in nuclear powered ships the cost of core and fuel rises with increasing power. Further, it is uneconomical,

both from the aspect of fuel expenditure and wear and tear on the ship's structure, to overdrive a surface ship, whatever the source of power, and increased speed will always, therefore, require a reduction in block coefficient. For each ship type there will be an optimum speed and block coefficient to suit her particular trade and the prevailing economic conditions. This optimum will vary with trade prosperity, and the ship form and speed should be chosen with an eye to economic trends, which involves a certain amount of long-range forecasting. For example, the optimum block coefficient for large oil tankers at the present low level of freight rates is in the region of ·81 with a corresponding speed/length ratio of about ·58. In a period of high freight rates the optimum block coefficient could fall as low as ·75 with correspondingly higher speeds. This argument has been discussed more fully in an article on the trend to supertankers[3].

The prospect is that nuclear ships will not differ greatly from the conventional in this respect. The machinery weight and space occupied by machinery will probably not increase with power at quite the same rate as that of conventional machinery, nor will the ships have to carry the increased weight of fuel, so one might say in very general terms that the optimum speed may be very slightly in excess, and the block coefficient slightly lower, than in corresponding conventionally powered ships.

### 5. Marine Reactors

It is hardly possible to discuss the design of nuclear ships without a brief reference to the elements of basic reactor design.

The reactor core usually comprises a number of fuel elements stacked in a geometrical arrangement to permit comparatively easy withdrawal. The fuel itself will generally be a compound of natural uranium, perhaps enriched with a small proportion of the radioactive isotope U-235, and enclosed in a "can". The canning material should have high temperature strength, be stable with respect to the fuel inside and the coolant outside and must have low neutron absorption characteristics. Control, shut down and "scram" rods of high neutron absorbing material are distributed at strategic positions throughout the core capable of withdrawal and insertion as desired, and also of shutting down the reactor automatically on development of a technical fault.

To utilise neutrons emitted from the core, it is first necessary to slow them down, and various mediums (moderators) are used for this purpose. Hydrogen is very efficient in this respect and its compounds, such as water and the polyphenyls are frequently found as moderators. It has the disadvantage, however, of absorbing many of the neutrons itself and for this reason enriched fuel is necessary for a hydrogen moderated reactor. Graphite is another efficient and cheap moderator with the additional advantage of low neutron absorption characteristics.

The coolant and heat transfer medium may be gas, liquid or liquid metal, and in some cases its function is combined with that of moderator. At present, the Society considers that direct cycle operation has not yet been sufficiently proven to permit acceptance and require heat exchangers with primary ducts to the reactor system and secondaries to the main turbines. The reactor core is enclosed in a pressure vessel which with the ducting to the heat exchangers comprises the primary circuit. The whole of the primary circuit (including heat exchangers) is contained within a larger pressure vessel (the containment vessel) designed to withstand the pressure and temperature generated by a nuclear accident of the worst kind and to contain fission products and possible missiles released during the accident. In the case of a marine reactor, this containment vessel will be supported within a gastight reactor compartment. There are therefore several stages of fission product containment through the fuel can, primary circuit, containment vessel and reactor compartment, but the containment vessel is regarded as the ultimate accident containment and the gastight reactor compartment is merely a precaution against slow gland leakages from the containment vessel after an internal accident.

Shielding is required round the primary circuit for protection against radioactive emissions, and secondary shielding is necessary round the containment vessel for protection in the event of an internal accident. Shielding is most efficiently provided by dense materials such as steel, lead and concrete, and contributes very largely to the high cost and weight of reactor systems.

The three reactor types fitted in the following ship designs are discussed briefly below.

The pressurised water reactor (P.W.R.) uses light water as moderator and coolant, pressurised to prevent boiling in the core. The system is compact but expensive, the principal difficulties arising from the high pressure in the system (of the order of 2,000 p.s.i.), corrosion, poor steam conditions, and the design and heavy scantlings of a containment vessel to provide for a primary circuit failure in such a high pressure system. The P.W.R. can be considered a proven reactor type and its reliability has been amply demonstrated by the expanding fleet of U.S. nuclear submarines.

The boiling water reactor (B.W.R.) is based on a similar concept and is a logical development of the P.W.R. The primary circuit pressure is reduced to permit limited boiling in the core, and when problems of safety associated with activity in the coolant are resolved, a direct power cycle should be possible, eliminating the necessity for heat exchangers. This reactor type is so far unproven at sea, the principal unresolved factor being the degree of hydrodynamic stability of the system when subjected to sea motions, as reactivity is affected by the percentage of voids (or steam bubbles) in the core.

The organic liquid moderated reactor (O.M.R.) uses a hydrocarbon, terphenyl, as coolant and moderator. Its principal advantage lies in its low

system pressure (up to about 300 p.s.i.) but disadvantages are a terphenyl fire hazard with certain proportions of oxygen (requiring the oxygen content of surrounding air spaces to be slightly lowered), solidification of terphenyl at room temperatures, and polymerisation of the coolant as a result of irradiation. The solid polymer must be filtered from the coolant and stored in shielded tanks in the ship for disposal on arrival at a suitable port. As a rough approximation, about a ton of polymer per day will be produced for every 20,000 to 25,000 developed h.p. A power organic reactor will be completed at Piqua, U.S.A., this year and zero energy experiments have been running successfully for some time. Much research and development remains to be carried out, however.

**6. The Nuclear Tanker**

Before going on to discuss problems relating to collision and the support of the containment vessel and its contents, it is proposed to examine briefly the principal features of three nuclear propelled ship designs.

Fig. 1 shows the lay-out for a B.W.R. powered tanker of about 65,000 tons deadweight and 20,000 s.h.p. The steam generated in the secondary side of the heat exchangers will be of relatively poor quality, necessitating an increase in overall size of the main machinery. The reactor pressure vessel, primary circuit and essential equipment is housed in a vertical cylindrical containment vessel 40 ft. in diameter, which is situated within a reactor compartment 48 ft. long. The main turbines and auxiliaries are situated in the 92 ft. long machinery space immediately aft of the reactor room. In accordance with the provisional rule requirements, a cofferdam 5 ft. in length is fitted immediately forward of the reactor space clear of the pump room, and the double bottom under the reactor compartment is 6 ft. in height.

The total length of machinery spaces in a conventionally powered tanker of this type (including settling tanks) would be of the order of 115 ft. to 120 ft. Including the cofferdam, the length of machinery spaces on the nuclear tanker is 145 ft. This poses quite a problem in longitudinal strength for the ship designer.

In oil tankers the greater part of the cargo deadweight is centred near amidships, giving rise to a sagging bending moment in still water in the loaded condition. In conventionally powered tankers, this sagging bending moment can be reduced, if necessary, by the provision of suitable ballast tanks which will be empty in the loaded condition. From the aspect of sagging, the most suitable place for these tanks is amidships, but the ship will then tend to trim by the head as the number of cargo tanks aft of midships is always less than the number forward. To satisfy the requirements of both strength and trim, these tanks are usually, therefore, situated just forward of midships.

Despite the high weight of reactor systems, the overall density of the machinery spaces and reactor room of a nuclear tanker will be much lower than that of any loaded cargo space. For example, the weight of cargo in the average tank across the ship may be of the order of 140 tons per foot of length in a large tanker, whereas the average weight of reactor and machinery for a heavy reactor system in the same tanker might be about 30 tons per foot or less. In the conventional tanker, fuel oil is carried towards the ends of the ship, and the sum of the weights of the machinery, boilers and oil fuel together in the departure condition will normally exceed the weight of a corresponding nuclear installation. In the arrival condition the combined weights will probably be about the same for both ships. So we might, if the lengths of machinery spaces were comparable, expect to find a slightly greater sag in nuclear ships. However, since a reactor system will occupy greater space aft than conventional boilers and oil fuel deep tanks, the cargo tank length aft of midships will be shortened, and further, since the cargo density is so much greater than the machinery density, this will tend to make the ship trim by the head. There are a number of methods of countering this undesirable trim, one or all of which may be used.

(i) The ballast tanks may be moved further forward, bearing in mind that this will increase the sagging bending moment, and increase the modulus requirements.

(ii) The ballast tanks may be increased in number and so arranged as to level the trim and maintain a desirable still water stress level. This has the obvious disadvantage of reducing cargo capacity.

(iii) The cargo tank length forward of midships may be reduced slightly, again increasing the sagging moment.

(iv) The longitudinal centre of buoyancy may be moved as far forward as practicable. Ship resistance characteristics and fineness of form aft will limit this movement to a maximum of about 2·1 per cent of the ship length forward of midships.

(v) The ship may be lengthened with the attendant disadvantages of higher capital cost.

So we see that, in the case of a tanker, the volume occupied by the machinery and reactor spaces are of equal, if not more, concern than the weight of the installation. The position and length of the cargo tank block are critical factors in the design and any forced reduction in the ratio of cargo tank length to ship length will introduce strength problems which may rely for their solution on the use of more ballast tanks. Capacity then becomes limited and in extreme cases could necessitate deepening or lengthening the ship. Of course, each design presents its own problems and most will be capable of solution without recourse to such drastic measures.

The particular design illustrated is a borderline case in which the weight of the reactor and machinery and the space occupied by them is such that the maximum permitted stress is not exceeded.

trim is level and capacity just available. The lesson to be learnt here is that for tankers, high density reactor and machinery lay-outs are essential for optimum ship design.

### 7. The Nuclear Passenger Ship

Fig. 2 shows an arrangement profile of a passenger ship used as an example in a paper recently given to the Joint Panel on Nuclear Marine Propulsion by the Society's Chief Surveyors[4]. This ship has a displacement of about 35,000 tons, a speed of 27 knots and maximum power requirements of 80,000 d.h.p. Three items of major interest will be immediately noted about this vessel. First that the modern trend of machinery towards the after end of the ship has been halted; secondly (although not shown in this arrangement), that the ship is equipped with two reactors in a single horizontal cylindrical containment vessel; and, thirdly, that the machinery and reactor spaces have been juxtaposed, turbo-electric drive being used.

From the strength aspect, the impact of nuclear power on passenger ships has a totally different effect from that on tankers, as the distribution of weights is quite dissimilar. In tankers the major item of weight is the cargo, but in passenger ships it is the main machinery and boilers. As passenger ships, due to their fine block coefficients and excess buoyancy amidships, normally hog in still water, any movement of the main machinery from the amidships position towards the after end will increase the hogging bending moment. If nuclear machinery is situated near the midship position, the increased weight of the installation over the conventional type will improve the stress conditions; if nuclear machinery instead of conventional machinery is fitted aft, the stress conditions will worsen considerably. Passenger ships powered conventionally carry large quantities of oil fuel in tanks spread over a considerable length of the ship and provision has to be made for the replacement of fuel oil as it is burnt, by ballast water which is usually carried in separate tanks. Nuclear passenger ships will carry hardly any oil fuel and the saving in weight, which may be of the order of 6,000 tons, will more than counterbalance the excess weight of the nuclear installation and protection structure.

Against the advantages from the strength point of view of siting the machinery amidships, must be placed the interruption of passenger spaces by the refuelling hatch and trunks. Although ventilation and access trunking is required to the conventional machinery spaces, siting the reactor aft of these spaces partly overcomes this objection and eliminates shafting and gearing difficulties due to the fineness of the ship aft.

The stability of a passenger ship, while not normally coming within the Society's province, is, of course, greatly affected by the omission of several thousand tons of liquids in the double bottoms. The centre of gravity of the reactor and machinery is also likely to be higher than that of boilers and machinery in a conventional ship, and the effect, therefore, is to increase the KG and decrease the GM for the same form of ship. Nuclear passenger ships, therefore, should have a higher KM than conventional passenger ships in order to give adequate stability in the intact and damaged conditions. The Safety of Life at Sea Conference in London (1960) required that nuclear passenger ships should have positive stability in the damaged condition with two adjacent compartments flooded. To achieve this, the BM can be increased directly by increasing the beam of the ship as the BM is approximately proportional to the square of the beam. Variations in draught will not affect the KM very much as, although the BM increases with reducing draught, the KB reduces. It is likely, however, that nuclear passenger ships will have somewhat less draught than their conventional sisters due to the large reduction in oil fuel, and the beam to draught ratio will increase. The normal beam to draught ratio of a passenger ship is in the region of 3·0 to 3·3, but nuclear ships are more likely to approach 3·8.

The effect of variation of beam to draught ratio on propulsion power is small if the displacement is unchanged. In general, the power required to drive a ship is a function of displacement and speed (without delving too deep into the mysteries of prismatics, wavemaking and propulsive efficiencies) within certain speed limits, and a convenient expression is

$$\text{Developed H.P.} = \frac{\triangle^{\frac{1}{2}} K^{3.2}}{100} \text{ where}$$

$\triangle$ is the displacement in tons and

K is the speed in knots.

The nicely-rounded denominator includes a factor for ship services, and the expression is approximately valid for the normal range of speeds up to $K/\sqrt{L} = 2(1{\cdot}08 - C_b)$ where $C_b$ is the block coefficient, and for most ship types. The Author, however, accepts no responsibility for failure to achieve contract speed!

Where only one reactor is fitted, an emergency alternative source of power will be required, but this can be dispensed with in the ship illustrated where twin reactors have been fitted. The weight disadvantage of twin reactors is in the region of 30 per cent—perhaps not as great as would be imagined, but the installation offers full utilisation with 50 per cent power in the event of a breakdown in one unit and a degree of dependability which the owner may favour. On the other hand, the risk of a nuclear accident is duplicated; the capital cost is considerably increased—about 50 per cent; and the prime cost of fuel is increased considerably. Against this should be set the fact that there is virtually no experience at present in the construction of a single reactor suitable for marine operation to deliver about 80,000 s.h.p. Dependability and schedule time keeping have to be weighed against the aspects of depreciation and running and maintenance costs. It is not intended to suggest that a reactor unit will be other than dependable when it has been built into a passenger

ship, but there is no doubt that, in the present state of technology, there is a good deal more to go wrong with such a unit than with a conventional boiler installation. In this case, dependability has been chosen as the more important factor.

This ship has been fitted with organic moderated reactors and provision has been made immediately aft of the reactor room for tanks to accommodate polymerised terphenyl, suitably shielded.

### 8. The Nuclear Passenger-Cargo Ship

The *Savannah,* the first nuclear ship to be built for commercial operation and constructed by the New York Shipbuilding Corporation, is now nearing completion. She is an enlarged version of the 20 knot Mariner class with a displacement of about 22,000 tons and carrying 60 passengers and 109 crew at a speed of 21 knots. Power is supplied by a pressurised water reactor of 69 M.W. output operating at 1,750 p.s.i. and producing steam at 465°F. and 451 p.s.i. to a cross compound turbine developing 22,000 s.h.p. at approximately 107 r.p.m. The uranium dioxide fuel in stainless steel cans has an enrichment of 4·4 per cent. The ship is also equipped with a 750 h.p. "take home" generator and small boiler of 7,500 pounds per hour capacity for hotel services. An arrangement profile of the ship is shown in Fig. 3.

The *Savannah,* of course, was not built to Lloyd's Register classification and a number of features will be observed which do not correspond with the Society's requirements. It has already been pointed out that this is a developing science, and that there should be differences of opinion at this stage is not, of course, surprising. It will be seen, for example, from Fig. 3 that no cofferdam separates the reactor room from the cargo spaces. Other points of difference are illustrated in Fig. 4 where it will be noted that heavy concrete is fitted all round the containment vessel. It is, in fact, only separated from it by a comparatively thin wooden pad. Fig. 5 (with concrete removed) shows how the longitudinal girder supports for the containment vessel are directly in line with the principal fore and aft members in the double bottom structure. The collision chocks based on B and C decks are trained directly on the shoulder of the containment vessel shell. Of course, at the moment, a design must depend largely on opinion, and opinions on structures of this kind vary considerably. But it is known that "edge-on" material is very efficient in resisting damage and, as such, it is perhaps taking a risk to provide through continuity between the possible source of an impact on the side shell or bottom and the containment vessel shell itself. The height of the double bottom in the *Savannah* is 5 ft. Further, it has recently been stated that the *Savannah* reactor components were designed on a basis of between 0·6 g and 0·7 g which indicates a considerable relaxation on the Society's 3 g requirement.

Having remarked on points of difference between the *Savannah* and the Society's provisional requirements, it should be pointed out that the design of the *Savannah* was commenced some time in 1956 when authorities in this country were just commencing paper studies on the construction of nuclear ships and, sad to relate, these studies have not yet passed the paper stage. Considering that the design was started so long ago, the United States Administration must be congratulated on the choice of ship and machinery. A cargo and passenger ship is ideal as an experimental test vehicle. When the *Savannah* was built, there was no pretence that economical operation could be achieved with this ship. What was required was operational experience, and only when this experience has been gained can ultimate nuclear ship economy be reasonably assessed. The type of reactor built into the *Savannah* is a proven type which has demonstrated its reliability time and again. Perhaps the only criticism which could be levelled five years after the original design concept is that this reactor type has almost reached its peak of development and that if a similar experiment were to be commenced to-day, a reactor system would be chosen with rather greater development potential.

The Safety of Life at Sea Conference last year required a Safety Assessment to be prepared for all nuclear ships indicating that the reactor installation did not constitute an undue hazard to passengers or public, or to waterways, or food or water resources. A copy of this Safety Assessment will be made available to the Port and Government Authorities of countries to which it is intended the nuclear ship will voyage. Parts of this Safety Assessment have already been prepared for the *Savannah* and received by the interested countries.

### 9. Collision and Grounding Protection

The containment vessel must be protected so far as possible, by good design and extra material strength, from penetration as a result of collision. The Society's Provisional Rules require the containment to be situated within a separate compartment which is not bounded by the side shell of the ship. Penetration can then only be effected by piercing the specially designed shell protection, the longitudinal bulkhead bounding the reactor compartment and finally the containment vessel shell itself.

So that the shell protection is given the opportunity to deflect and develop membrane strength and so absorb energy, the Rules require that at least 5 ft. should separate the longitudinal bulkhead from the inner face of the primary ship side supporting members, and that a similar distance should separate the bulkhead from the containment vessel. These figures fix the approximate location of the bulkhead. From the aspect of longitudinal strength, the bulkhead should be in line with similar longitudinal material elsewhere in the ship. Subject to the minimum distances

given above, the containment vessel shell should be not less than B/5 inboard of the ship's side at the load water line, where B is the breadth of the ship.

Recent Japanese experiments[5] on the collision resistance of ship side structures suggest that the influence of shell thickness on collision resistance could be considerable. These experiments were carried out on 1/20 scale models with varying shell thicknesses and differing girder arrangements. The experiments carried out with thick shell plating resulted in a much reduced penetration of the struck ship and a correspondingly greater amount of damage in the bow structure of the striking ship. The same bow structure was used for all the tests. This result contradicts data obtained from actual ship collisions so far as they can be correlated, as in these cases the resistive effects of the shell appeared comparatively small, most damage being inflicted on the bow structure by horizontal edge-on material such as decks. The contradiction could well be explained by scale effect. Structures fail in varying modes—shear failure, buckling and crippling, pure tensile failure, brittle fracture, etc.—but these are not all dependent on the same parameters. A reduction in scale, apart from increasing the influence of welded connections, would affect the probability of a given type of failure occurring, so that one mode of failure might easily be replaced by another mode on a different linear scale.

The Society, too, is carrying out experiments at Crawley, principally, for the moment, on the modes of failure of edge-on plating. The more damage that can be inflicted on the bow of the striking ship, the less damage will be incurred by the struck ship, and recent cases of collisions have shown that where the striking ship is fast with a relatively fine bow entrance angle, decks in the struck ship will slice through the bow structure causing considerable damage. The bows of slow ships with bluff entrance angles are more likely to collapse on themselves.

Fig. 6 (a) (from reference 4) shows a proposal for the design of side shell protection. The purpose is to stop the oncoming ship with respect to the struck ship before penetration exceeds 1/5 of the beam, and it is considered that, using the weakest possible mode of failure as a criterion, this type of structure could perform this function satisfactorily against a ship of the ocean liner class.

The extent of damage and depth of penetration caused by a collision will depend on the velocity and displacement of the colliding ships and the resistance to damage of the bow of the striking ship and that of the side structure of the struck ship. The movements of each ship during and subsequent to collision are defined by the principles of conservation of energy and momentum, both linear and angular, in terms of the structural resistance to damage. A perfectly elastic collision is one in which neither momentum nor energy is lost, and by solving the momentum and energy equations simultaneously, the final velocities after collision are completely defined. A perfectly elastic collision between two ships is not possible, as momentum and energy are absorbed by the forces causing damage, by water resistance, by vibration and by the rolling motions and elastic deflection experienced by both ships. Momentum can be absorbed by a force of retardation over a given period and the amount of momentum so lost is represented by the area under the force-time curve, or

$$\int_{0}^{t} F.dt$$

Similarly, energy can be absorbed by a retarding force over a given distance and is represented by the area under the force-distance curve, or

$$\int_{0}^{s} F.ds$$

In addition, a body moving through a liquid with other than constant velocity has associated with it an entrained mass of liquid, the amount of which appears to be a function only of body shape, direction of motion and liquid density. So a ship in collision which alters its direction of motion as a result of the collision will carry with it an entrained mass of water. Saunders[6] considers that this mass will be of the same order as the mass of the ship itself if it is moving in a broadside direction.

There is, therefore, a relationship between the resistance to damage of the ship structures and the final ship velocities, but either must be known before the other can be deduced.

It is important in the design of collision resistance structures that the material used to limit the effects of collision should not be supported by the containment vessel shell.

Grounding accidents are usually of a minor nature and permanent grounding and severe damage in large ships are relatively rare occurrences. In general, moderate grounding damage will be absorbed in the double bottom structure, with little or no damage to the tank top. Severe local damage in way of the reactor supports, however, with attendant displacement of the tank top can be absorbed in the containment supporting structure if it is designed on the principles outlined below.

**10. Support of the Containment Vessel**

The containment vessel should be supported in such a way that the bottom shell of the ship should be capable of sustaining comparatively severe local damage in the vicinity of the reactor room without prejudicing the support of the reactor and its relative position in the ship. Further, the containment should not form part of the hull structure, and should be constructed in such a way that the transmission of stresses between the hull structure and the containment vessel is reduced to a minimum.

Before considering how this can be done, the shape of the containment vessel must be decided.

There are four principal factors influencing the design of the vessel, namely:—

(i) Its ability to withstand an internal pressure satisfactorily;

(ii) the design of the reactor pressure vessel, primary circuit and associated equipment which will be contained within it;

(iii) the optimum use of available space, and

(iv) its compatibility with the surrounding ship structure.

From the pressure vessel aspect, the most satisfactory design is spherical. This is, however, prodigal in the use of available space and will normally require support in the form of a skirt with radial stiffening.

The most common pressure vessel shape is cylindrical with hemi- or torispherical ends and this design will probably be found most convenient from the aspect of the reactor engineer.

Basically, there are two systems of plane stiffening—that with radial and concentric members and the orthogonal system such as is found in ship type structures. If one of these systems is directly superimposed on the other, "hard spots" and stress concentrations will occur at the intersections of the crossing members. In containments which are supported by a radial system of stiffening, this incompatibility has to be eliminated by very careful design.

From the aspect of maintaining the support of the reactor despite severe localised damage on the ship's bottom, shear failure devices or a multi-support system will require to be used.

There are many ways of achieving a satisfactory design of containment support and one of these is shown in Fig. 6 (a). In this case, the close-spaced transverse floors and the centre girder in the double bottom under the reactor compartment are lapped to provide a local overload failure device and deep T-section longitudinals provide an additional reserve of bending strength on the bottom shell and tank top. The main shell transverses are mirrored on the inside of the longitudinal bulkhead, and swept upwards to form a cradle for the containment vessel. These cradle webs subtend the lower quarter of the periphery of the vessel and terminate 12 in. clear of the shell of the vessel. To satisfy the Society's external design pressure requirement of 50 p.s.i. for containment vessels, external ribs are fitted and these are utilised for the support of the vessel by spacing them the same distance apart as the main ship transverses. Over the lower part of the periphery the rings are split into pairs and the method of attachment of the webs is indicated in Fig. 6 (b).

In this case, there are no friction surfaces and the vessel is connected indirectly to the ship's structure by welding all along its length. The flexibility of the webs, however, is such as to accommodate easily all possible expansion in the length of the vessel.

More than sufficient material and weld area is provided to satisfy the Society's acceleration requirements. The worst condition is experienced when the ship is inclined to 90°, when the yield stress will be slightly exceeded. At this stage, it is unlikely that the structure will be required for further duty! The cradle supports are adequate to support the vessel under any conditions of roll, impact or list.

Of course, this is only one of many solutions to the support problem. The *Savannah,* for example, employs a friction bearing type of support.

## 11. Conclusion

Studies relating to the design and construction of nuclear powered ships have been proceeding in all the major shipbuilding countries of the world in recent years. So far, the only projects to have been carried into practice are those of the *Savannah* and the Russian icebreaker *Lenin*. The latter, of course, is a ship built for a very specialised purpose and one for which we in this country have no market. It is, however, probably the only application of nuclear power to non-military marine purposes which will pay dividends in this decade, and that because of its phenomenal endurance compared with conventionally powered ships of the same type. But, in general, nuclear energy will remain an unprofitable source of power for merchant ships for many years to come. There is no doubt that safe nuclear ships can be built and operated but the capital bound up in sheer "ironmongery" will deter private investors from embarking on such an enterprise. So if nuclear ships are to be built for experiment and experience, the capital will almost certainly be provided by the government of the country concerned as has happened in the U.S. and U.S.S.R.

The shipbuilding and engineering of a nuclear ship will involve fresh techniques and the purchase of new equipment and many mistakes will be made at first. As more are built, costs will go down and engineering design and methods improve. Operating experience will indicate safe and economic methods of fuelling and defuelling and dispel the present fog surrounding port procedures. This is where an experimental ship like *Savannah* can pave the way for more concrete economic assessments than are now available.

Advances in engineering techniques are limited by safety considerations. It might be possible in the future to dispense with containment altogether by the use of quenching methods so that the residual accident pressure could be contained in the hull structure and this would reduce weight and space requirements and lower capital costs considerably.

The biological problem will always remain for fission type reactors with the attendant high weight and cost of shielding. Naval architects and marine engineers must look forward to the major breakthrough in the field of physics which will provide fusion reactors and the almost complete elimination of the biological problem.

## 12. Acknowledgments



The Author is indebted to the Chief Surveyors for their permission to use material and diagrams from their recent paper to the Joint Nuclear Marine Panel, and to the U.S. Atomic Energy Commission for the supply of slides and sketches relating to the N.S. *Savannah*.

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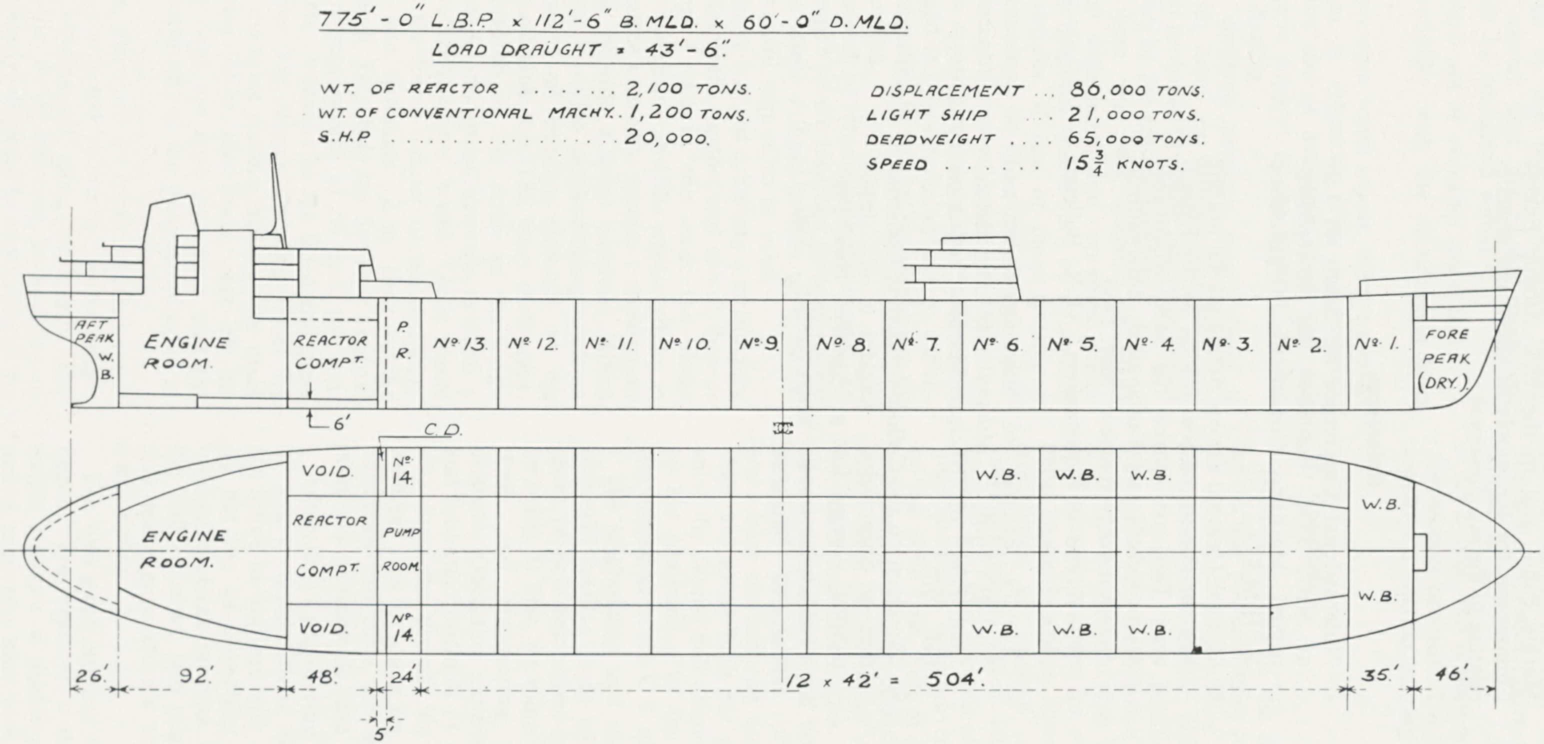


ARRANGEMENT OF NUCLEAR-POWERED TANKER.

FIG. 1.

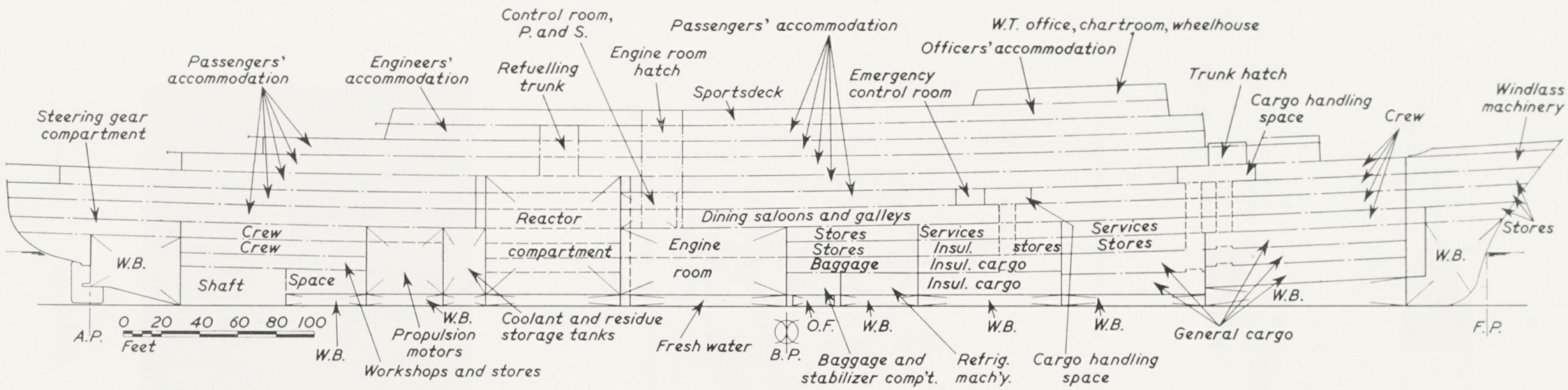


Fig. 2

Arrangement Profile of Proposed Passenger Ship

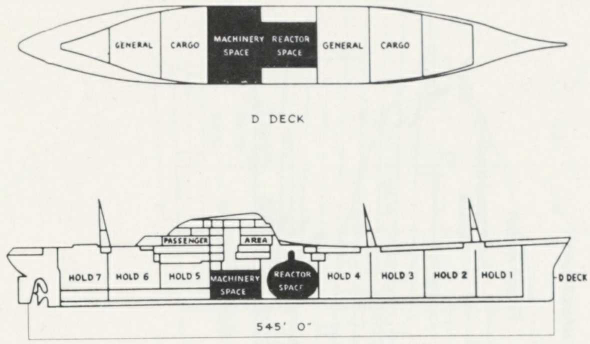


Fig. 3

General arrangement, *Savannah*

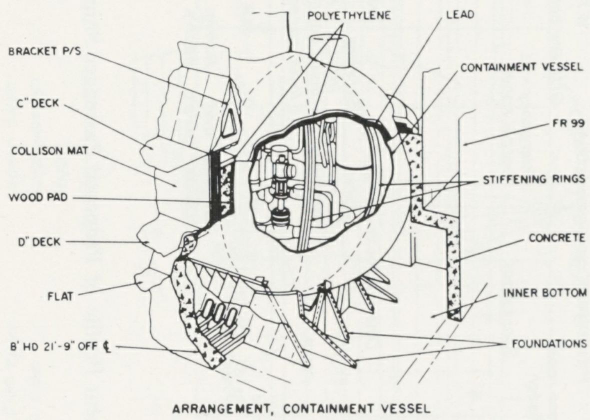


Fig. 4

*Savannah*

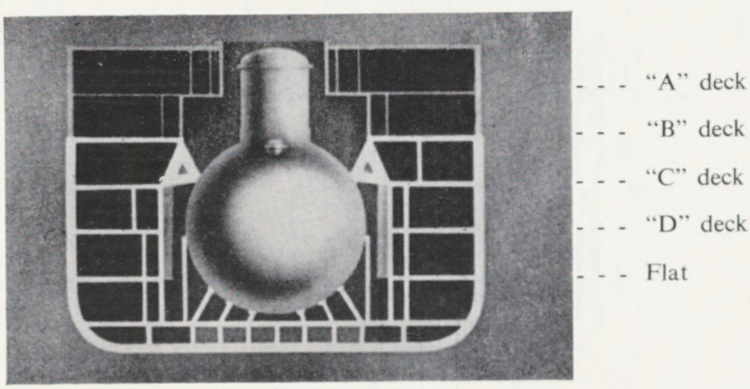


Fig. 5

Section through reactor space, *Savannah*

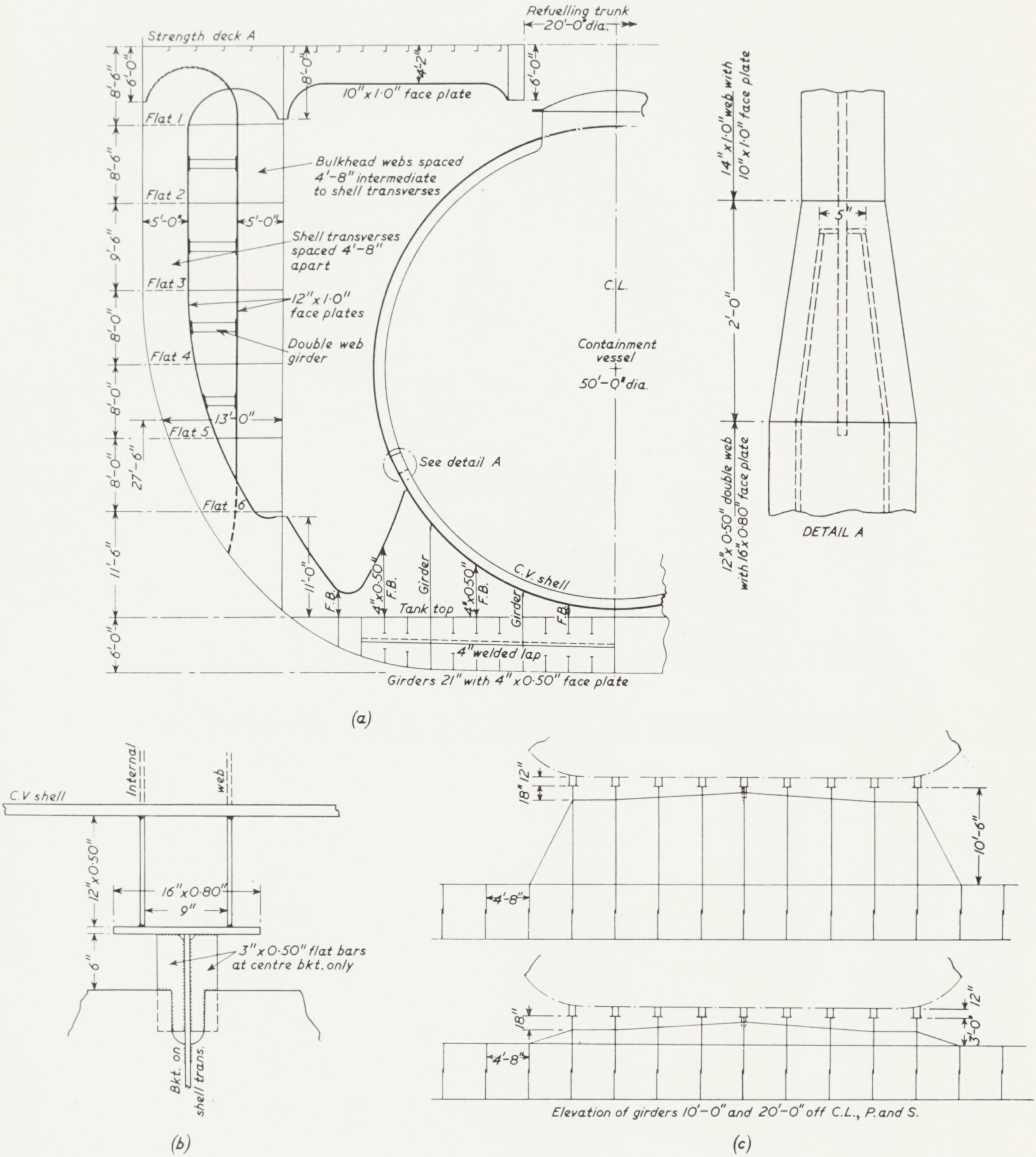


Fig. 6
Collision Protection and Containment Vessel Support

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at Garrett House
Manor Royal, Crawley, Sussex, England

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# Lloyd's Register Staff Association

Session 1960 - 61

Paper No. 6

## Discussion

on

Mr. J. McCallum's Paper

# THE DESIGN AND CLASSIFICATION OF A NUCLEAR POWERED SHIP

LLOYD'S REGISTER OF SHIPPING

71, Fenchurch Street, LONDON, E.C.3

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Discussion on

Mr. J. McCallum's Paper

# The Design and Classification of a Nuclear Powered Ship

### Mr. J. B. DAVIES

Mr. McCallum is to be congratulated on giving us a most lucid paper on a very involved subject. The paper must be nearly unique in that I cannot think of another paper on the subject with so few formulæ!

The Author has kept clear of the dangerous field of economics and has clearly brought out the various problems which we will have to face should an owner decide, either on grounds of economics or for prestige, to build a nuclear powered merchant ship. As he has said, the Society's Rules give ample guidance as to the standards required although I can well imagine an argument developing as to whether, in a vessel which is well designed with a low still-water bending moment, the 10 per cent increase in longitudinal strength is really necessary.

When discussing the design of a nuclear powered tanker the Author draws attention to a point which is easily forgotten ; despite the heavy weights associated with shielding, etc., the weight per foot length is relatively low and the nuclear installation requires a large space which must be entirely at the aft end and cannot readily be divided, in the way that a conventional tanker will have machinery and some fuel aft and the remainder of the fuel forward. A minor point is that nuclear tankers will not be able to take much advantage of the tropical load line. Most tankers load in the tropical zone and the conventional tanker can carry an increased cargo deadweight equal to the amount of fuel she will use before reaching the summer zone.

However safe one may make the reactor space as regards normal operating conditions there is obviously always a danger that it will be penetrated in a collision and the experiments being carried out at Crawley should be of great assistance in determining how the shell protection can best be designed to minimise this risk.

### Mr. O. M. CLEMMETSEN

First I would like to congratulate Mr. McCallum on producing such a concise account of the difficulties which must be overcome in designing a nuclear ship, and especially for the fact that he has managed to do this with the use of only two integral signs. However, I fear that this is only the thin end of the wedge as far as the mathematics of the problem are concerned, since in the recent paper by Mr. Murray and Mr. Pemberton on the same subject there were no integral signs at all. There must be few shipbuilders who have previously designed a ship for collision resistance, but that is evidently what is before us, and I believe quite a large portion of Mr. McCallum's time has been taken up with analysis of such collision data as is available.

I notice that in the Provisional Rules for Nuclear Ships resistance to collision damage is to be assessed in the design stage and perhaps Mr. McCallum could say whether this is intended to be qualitative or quantitative, and if the latter, what sort of criterion is envisaged.

Taking the broad view of the paper, it seems to me that Mr. McCallum takes a rather gloomy view of the prospects for the nuclear ship, principally on economic grounds. However, since material prestige is unfortunately considered so important nowadays, it seems that Britain will have to build a nuclear powered ship if it is to remain a leading shipbuilding nation, even though the advantages of such a procedure may only consist of finding out the disadvantages, as it were. I suppose we can take comfort that things looked much the same to the pioneers of the steamship when they were competing with the sailing ship whose motive power, the wind, was provided free. However, from the closing remarks in the paper, it seems that an entirely different picture will present itself if a suitable fusion reactor is developed, though I doubt whether we can wait for such a development before proceeding with the construction of a nuclear ship. The fusion reactor would, I assume, mean the absence of the problem of disposal of radiation products, but perhaps Mr. McCallum could confirm this.

Turning to more specific points from the paper I should like to ask the following: —

(1) What degree of permeability is envisaged in the two-compartment standard of sub-division recommended by the 1960 Safety Conference, and does this depend on a criterion of service?

(2) Although the weight of nuclear machinery as a whole is apparently to be less than that of conventional machinery plus fuel, the weight in the region of the reactor compartment is probably high. In ships with machinery aft, where the difference between weight and buoyancy will be greater than where the machinery is amidships, are high shear stresses likely to be developed?

(3) Is the fission process and circulation in the primary circuit affected by rolling of the ship?

(4) In the passenger ship it is noted that two reactors are fitted in a single containment vessel. In the event of a breakdown in one reactor involving release of radiation products, could the other reactor be affected? Is the containment vessel never entered except for servicing, and how often is this servicing necessary?

(5) With regard to the loss of stability in a nuclear passenger ship due to the loss of liquids in the double bottom, if in a given case the fitting of solid ballast is considered more desirable than altering the beam and draught, there would appear to be some scope for completely filling the tanks affected by plastic foam, which, if it could be supplied with a suitable density, might obviate the necessity of fitting permanent ballast and examining the double bottom tanks at survey, and could possibly provide additional grounding protection. In any case, if there are to be a number of double bottom tanks permanently empty, filling with normal plastic foam might be an advantage from the survey viewpoint.

(6) Does the requirement that 5 ft. should separate the longitudinal bulkhead in way of the containment vessel from the primary ship side supporting members refer to the stiffening of the longitudinal bulkhead, if this is fitted in the side cofferdam, or is it the distance measured to the bulkhead plating?

(7) Since the clearance between containment vessel and ship's side is to be B/5 port and starboard, the maximum diameter of containment vessel is 3/5 B. There is therefore a minimum beam corresponding to a given size of reactor. Is this likely to restrict the size of ship in which a reactor could be fitted or is it anticipated no ship will be provided with nuclear power of a length to be affected by this requirement?

### Mr. G. M. Boyd

The containment vessel seems to be a highly expensive item, and I presume that the experts have fully considered whether it is really necessary. If it is merely a precaution against a nuclear accident, the probability of such an accident would no doubt be considered, and the vessel could be designed on a "once only" service basis.

It would seem that nuclear tankers would have to be considered even more carefully than other types of ship owing to the risk of explosions and fires, particularly in port.

Has consideration been given to the possibility of "dumping" the whole reactor in case of a nuclear accident?

### Mr. G. de Wilde

A number of times during the discussion the word risk has been mentioned and the desirability to reduce the risk of various forms of damage occurring in a nuclear powered ship. Obviously the 10 per cent increase in section modulus over the normal Rule requirement has been introduced to reduce the risk of damage due to longitudinal bending. Increasing the section modulus does not mean that a certain stress will no longer be reached, only the frequency of occurrence of that stress has been reduced. By how much depends on the long-term probability distribution of the stresses.

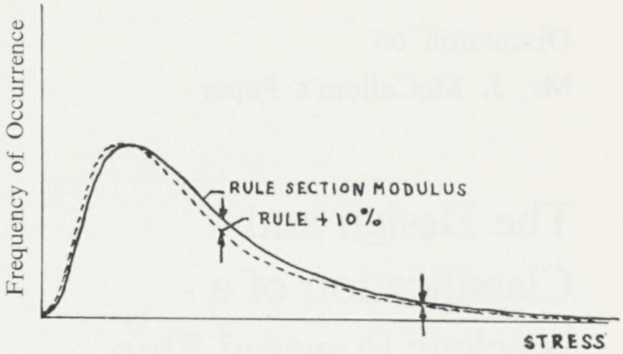


Fig. 7

For the higher stresses the reduction in frequency of occurrence is something like from 0·02 per cent to 0·01 per cent. At the steepest part of the curve the drop is about 6 per cent.

The general stress level is, of course, reduced by 10 per cent.

The reduction in damage incidence caused by this reduction in general stress level depends on the initial stress level.

When the stress is brought down from $\sigma_1$ to $0{\cdot}9\sigma_1$ a considerable reduction in damage incidence will result. A reduction in stress from $\sigma_2$ to $0{\cdot}9\sigma_2$, however, will have very little effect.

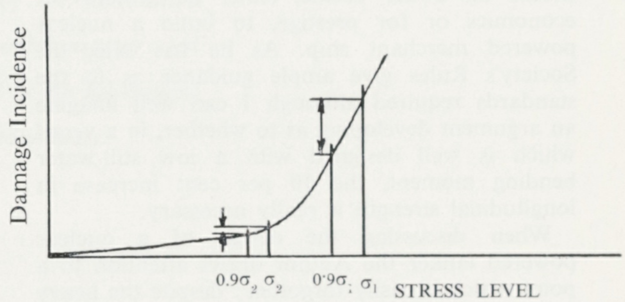


Fig. 8

It may be expected that the acceptable Rule stress will be at $\sigma_2$ where the curve starts rising steeply so that a 10 per cent reduction below Rule stress may be a high price to pay for a relatively small reduction in damage incidence.

### Mr. J. Macleod

In recent discussions on Nuclear Propulsion for Ships it would appear that the gas-cooled graphite-moderated reactor, if not neglected, is certainly left in the background.

In view of the real advantage of higher steam temperatures associated with this type of reactor, its stability under sea-going conditions compared with reactors containing liquids, and also the experience we have in this country of this type, I would have expected one of this type to be mentioned in an example design.

Is this omission of any particular significance? Does the Author feel that the types mentioned in his paper show more promise than the gas-cooled reactor?

Mr. B. HILDREW

There are a number of general statements in this paper which the Author might be prepared to give a further opinion on.

In Section 1 it is stated that economic parity with a conventional ship will be first achieved with a passenger-ship type. However, the Author suggests that safety requirements will have to be proved in another type of ship. He has made no comment on the potential explosion hazard inherent in a tanker or on the ability of any particular tanker hull design to withstand an explosion. Conventional experience relating to protection of an installation against possible external hazards indicates that a preferred first nuclear ship should be built for any trade except ammunition and oil and the additional safety requirements imposed on a passenger ship suggests that this particular ship type is best suited to the experiment of nuclear propulsion.

In Section 3, when discussing the Provisional Rules for Nuclear Ships, it is noted that the scantlings of the deck and shell are to be such that the longitudinal strength of the ship exceeds by 10 per cent the requirements of the rules for the class of ship. Could the Author explain more fully this requirement which appears to reflect upon the safety of the conventional ship?

It is stated in Section 4 that if freight rates rise block coefficients fall and vice versa. How is it possible for an owner to decide when ordering a ship that the block coefficient is suited to the economic trend three years hence? Does the owner also consider what is the average block coefficient best suited to a twenty-year operating life of the hull?

In Section 5 the Author's comment that direct cycle has not been proven sufficiently for installation in a ship should not be read as an absolute rejection of a direct cycle reactor installation.

Experience on shore is rapidly filling in all the gaps in so far as this reactor type is concerned, except the problem of stability in a seaway. This particular problem has been attacked from a number of directions and recent published information on the operational experience of the direct cycle BWR at Valecitos indicates that the Society would have to give serious consideration to a proposal of a direct cycle BWR in a classed ship. At this stage in development it is probable that such an installation would be operated as a research experimental facility and it is in this context that the Society could examine the proposal.

After examining the economics of a direct cycle installation an owner might not be attracted to it as the limited access to the main engines at full power and the additional shielding required offset the apparent advantage of this reactor concept.

The statement at the end of Section 5 is not strictly true as it suggests that the experience of the organic liquid moderated reactor has only been obtained from zero energy installations. The work at the Organic Moderated Reactor Establishment (OMRE) is carried out on a 12 MW installation and the operational parameters are directly related to heat transfer rates and coolant stability expected to obtain in a large power reactor.

Section 6 suggests that Fig. 1 shows the layout for a BWR installation, but in so far as a tanker is concerned this is irrelevant as both a PWR and a OLMR would occupy a similar space in the hull.

The pros and cons of a two-reactor installation referred to in Section 7 are open to argument. The provision of two reactors may duplicate the risk of a nuclear accident, but this is not the normal attitude adopted when the double banking of a piece of plant occurs. In the event of a nuclear accident it is relatively easy to design a protection between the two reactors to localise damage in the unlikely event of disruption of a reactor pressure vessel.

Another advantage of the two-reactor system is a reduction in the height of the installation, with consequent greater ease of installation, servicing and refuelling in the reactor compartment. The increase in fuel costs will only be marginal and not considerable as suggested.

The conclusion that any nuclear ship must be dependent wholly on Government capital is not a healthy prospect as it is desirable that private enterprise be involved in some degree of responsibility in any merchant marine project in order that the experience obtained from the end product can be truly related to a Merchant Navy.

## AUTHOR'S REPLY

To Mr. J. B. Davies

Not many papers have been published which deal solely with the ship design aspect of nuclear propulsion, but, no doubt, the formulæ will increase in numbers by geometrical progression with each new publication. Frankly, it is much too early to circumscribe fluency of design by restrictive formulæ—which is an elegant way of saying that there is not enough data yet to be completely definitive.

So far as the economic field is concerned, there is no danger of contradiction in saying that nuclear ships to-day are quite uncompetitive and that if they were built it would be for development or prestige.

As Mr. Davies suggests, it is not uncommon to become involved in a "ten-per-cent" discussion. Opinions are about equally divided among shipowners on this point, and, oddly enough, by nationalities. In general, British shipowners tend to agree that 10 per cent is a small price to pay for additional security.

To Mr. O. M. Clemmetsen

At the moment, assessment of resistance to collision is a very inexact procedure. The point of application and direction of the impact are all-important but unknown. So it must be assumed that the load is applied at the weakest link in the

structure. Similarly, collapse mechanisms must be assumed to occur by the simplest minimum energy mode. It is a sobering thought that a ship's structure can make up its mind in about two seconds just how it will fail under any given circumstances. At present, mere humans are not gifted with this faculty, and are only able to provide a very rough estimate of collision resistance for any given structure. The Author would prefer to regard this as a "qualitative" assessment, with the promise of better things in the future when some of the experiments have come to fruition.

It is not necessary to read this paper to sense the air of gloom and frustration which pervades marine nuclear projects in this country. To coin Mr. Clemmetsen's phraseology, few think it worth while even building a nuclear ship to find out the disadvantages. Perhaps the moon is a more entrancing objective. The analogy to the pioneers of the steamship in the days of sail is, however, not quite a parallel to that of the nuclear ship. It was possible to show a greater theoretical profit for the steamship against sail. A profit can be shown on paper for nuclear ships but not as great as that which can be gained from conventionally powered ships until very large ships are considered, and the incentive is thus lacking. One can very well see the point of the shipowner's view that there is no reason to introduce an additional risk factor unless the profits are to be considerably greater.

In the case of a fusion reactor, radiation hazards would be almost eliminated with consequent all-round improvement and reduction in weight.

There has been no change relevant to nuclear ships in the wording of the clauses relating to permeability as a result of the 1960 London Conference. Perhaps the phraseology is not as clear as it could be, and the Author is aware of a case where three quite distinct interpretations were imputed.

To the best of the Author's knowledge, no ship has ever failed as a direct result of shearing forces, but, as noted in the paper, machinery weights are considerably less than those normally carried in an equivalent cargo compartment in a tanker or ore carrier. It is not anticipated that shearing loads will be a critical factor.

Instability could occur in the core of boiling water reactors due to the quantity of steam voids being affected by the motions of the platform. This would give rise to power surges which would be an embarrassment if the motions were periodic and synchronous with reactor response. This is the subject of investigations now proceeding, but it is predicted that the findings will be favourable provided that the core is designed with platform instability in mind. Circulation in the circuit will not be affected by periodic motions. Natural circulation is usually provided to operate at large angles of heel to remove decay heat in the event of failure of all circulating and stand-by pumps.

It depends entirely on reactor type and design under what conditions the containment vessel may be entered. It will certainly be necessary to examine components in the containment during surveys at two-yearly intervals, but one recent design permitted limited work to proceed within the containment while the reactor was at full power. Normally, it should not be necessary to enter the containment except at surveys, and in such a case there is no reason that two reactors should not be fitted in a single containment. It would be ensured, of course, that missiles generated by an accident in one system could not penetrate the other.

Mr. Clemmetsen's proposal for filling double bottom tanks with plastic foam seems very sound.

The minimum distance of 5 ft. given in the Rules is measured from the longitudinal bulkhead plating.

It is unlikely that very small ships will be powered by reactors for some time to come, by which time more information should be available on the optimum form of side protection. Even under the present requirements, however, it should be feasible to fit reactors in ships down to about 300 ft. in length.

To Mr. G. M. Boyd

The containment vessel represents quite a large proportion of the cost of a nuclear installation and considerable attention is being directed to the possibility of dispensing with it by using pressure suppression techniques. The principal function of the containment is to prevent the escape of fission products to the atmosphere in the event of a nuclear accident. High pressures and temperatures could be generated within a very brief space of time and the design of the vessel is based on an assessment of the major accident condition. The internal design pressure is normally the major accident pressure, and the external design pressure 50 p.s.i.; the design stress must not exceed the lesser of $\frac{2}{3}$ of the yield stress (or the 0·2 per cent proof stress) or $\frac{1}{3}$ of the ultimate tensile stress. The effects of an uncontained nuclear accident are hardly such as to justify the appellation "merely a precaution"!

Apart from the difficulties of designing a marine reactor so that it would be "dumped" in case of accident, the dumping would have to take place in deep water. Criticality accidents have an unhappy knack of occurring in a matter of seconds, and it would be impossible in such a case to choose the dumping site.

To Mr. G. de Wilde

Mr. de Wilde's remarks on statistical considerations are much appreciated, but the Author doubts their validity. In the field considered, namely, the larger type of ship classed with Lloyd's Register, the maximum nominal stress (still water plus wave) is usually of the order of 9 or 10 tons per sq. in., so that all these ships lie in a narrow vertical band on Fig. 8. Subject to service variations, the incidence of nominal or other stress levels should be about equal for all. The element of comparison between low and high stress levels is therefore absent.

To Mr. J. Macleod

All reactor types showing a hint of promise for nuclear marine propulsion have been eagerly examined and the gas-cooled graphite-moderated system was no exception. All systems have some advantages and some disadvantages. The gas-cooled reactor was developed in the U.K. as a land-based reactor but recent developments in design have indicated its possibilities as a marine reactor. In general, however, against higher steam temperatures must be balanced comparatively high weight and cost and the complexity and fragility of the graphite core. The high-temperature gas-cooled reactor shows some promise for the future. The paper, however, dealt only with broad types which are presently considered most eligible for the purpose.

To Mr. B. Hildrew

The Author agrees completely with Mr. Hildrew that a large passenger ship type is best suited to nuclear propulsion and suggests that an ore carrier would probably be the most promising vehicle for an experiment.

The 10 per cent increase in minimum modulus for nuclear ships carries no imputation that conventionally powered ships are inadequate. There are cases (some passenger ships, for example), where no increase in scantlings would be necessary to fulfil this condition. In the other cases it should be remembered that reinforcement against collision and grounding damage will necessitate an increase in modulus of at least 10 per cent in the region of the reactor compartment, and for some distance forward and aft of the containment. Continuity in ship design is an essential feature and the increase in modulus over the remainder of the half-length will reduce non-uniformity of section and hence the incidence of stress concentrations. A 10 per cent increase in modulus over such a proportion of the ship's length represents a very small increase in the capital cost.

The Author referred in section 4 to optimum block coefficients—that is, the most advantageous block coefficient from the economic aspect. The ability to assess economic and trade trends is the essence of successful ship operation.

In general, the Author agrees with Mr. Hildrew's remarks on direct cycle operation and the O.L.M.R. Regarding twin reactors, there are obviously advantages and disadvantages, but double banking reactors in this context is hardly comparable with double banking other vulnerable components.

If private enterprise can be persuaded to embark on nuclear propulsion without state aid, the Author would be pleasantly surprised.

The design of nuclear ships is very much a combined operation between engineers and naval architects and this is, perhaps, the appropriate moment for the Author to place on record his appreciation of the assistance and co-operation he has received from Mr. Hildrew and his engineering colleagues in all phases of the Society's work in this field. He would also record his appreciation and thanks to all who participated in the discussion.

PRINTED BY LLOYD'S REGISTER OF SHIPPING
AT GARRETT HOUSE
MANOR ROYAL, CRAWLEY, SUSSEX, ENGLAND